Insects and Disease/Injury

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ROOT DISEASE, LONGLEAF PINE MORTALITY, AND PRESCRIBED BURNING

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Abstract–A study was initiated at the Savannah River Site, New Ellenton, SC, to determine factors involved in decline of longleaf pine associated with prescribed burning. Pretreatment and post-treatment surveys were conducted on all treatment plots. Symptomatic trees were recorded by means of a crown rating system based upon symptom severity. Three years after prescribed burning treatments were initiated, mortality and numbers of symptomatic trees increased in the hot burn plots. Crown symptoms corresponded to tree physiological status determined by cambial sucrose synthase activity. Root pathogenic fungi such as *Leptographium terebrantis*, *L. procerum*, and *Heterobasidion annosum* were widespread throughout the study site, regardless of treatment. The *Leptographium* species were found to be pathogenic based upon inoculation experiments and *H. annosum* was observed to be involved in root infections and mortality. Histological studies indicated a high fine root mortality rate in the hot burn treatment. The decline syndrome on these sites is a complex of interacting factors and involves root pathogens, soil factors, root damage, and physiological dysfunction.

INTRODUCTION

Although the beneficial role of fire is well documented for longleaf pine *(Pinus palustris* Mill.), little is known about fire's biological effects, whether prescribed or wild. We do know that a large portion of the above-ground biomass can be altered or lost without significant mortality of seedlings or adult trees. Saplings of longleaf pines are in continuous flush in height growth and are vulnerable to fire and disease (Allen and Scarbrough 1969). On the other hand, field observations report a high mortality rate in adult longleaf pine that continues several years after prescribed burning. Also, recent studies have indicated certain root-infecting fungi such as *Leptographium* species, other Ophiostomatoid species, and *Heterobasidion annosum* (Fr.) Bref. are associated with declining longleaf pine (Otrosina and others 1995, Otrosina 1998, Otrosina and others 1999). This contrasts with the generally held notion that longleaf pine is resistant or highly tolerant to many diseases and insects that adversely affect other southern pine species (Derr 1966, Mann 1969).

Questions arise as to why, in a tree species adapted to frequent fires, are decline and mortality associated with prescribed burning? This study addresses anatomical, pathological, and physiological processes as they relate to fire intensity and identifies areas needing further investigation.

MATERIALS AND METHODS

The study area was selected on the Savannah River Site in Barnwell County near New Ellenton, SC. A 40-year-old planted stand of longleaf pine was subjected to four burning treatments in a randomized complete block design. Each 2.0-ha treatment plot was replicated four times with unburned check, cool, medium, and hot burn intensities randomly assigned. Four 0.0079-ha subplots were located in each plot starting with one at plot center and three others located 30 m from plot center at 120° intervals starting from due north.

Prior to burning, a 100 percent survey was conducted on all plots to document current mortality and symptomatic trees. Burning took place between January and March 1997. Burn temperature was regulated by monitoring fuel moisture sticks, wind speed, and days since precipitation prior to ignition. Temperature data was obtained from max-min thermometers that were placed between the duff layer and mineral soil interface in four evenly spaced locations on each burn plot. The low and medium intensity burns were head fires while the hot burn was a backing fire tending to move more slowly across the landscape. Fuel data by fuel type were obtained according to Savannah River Forest Station fire crew protocols.

Starting one month post treatment and periodically thereafter, 100 percent surveys were conducted on all plots for three years. We employed a slight modification of a crown rating system used previously for longleaf pine symptoms (Otrosina and others 1999). The present rating system consists of five progressively symptomatic crown classes, differing from the previous system by adding a healthy class (class 0) and defining four symptom classes instead

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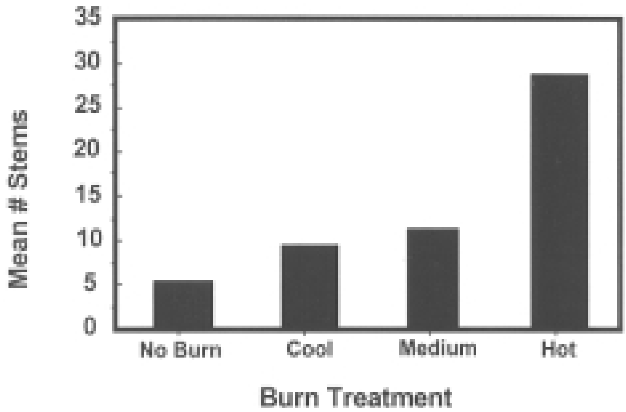

Figure 1a—Mean number of dead longleaf pine stems three years after burn treatments. The hot burn had the largest overall mortality.

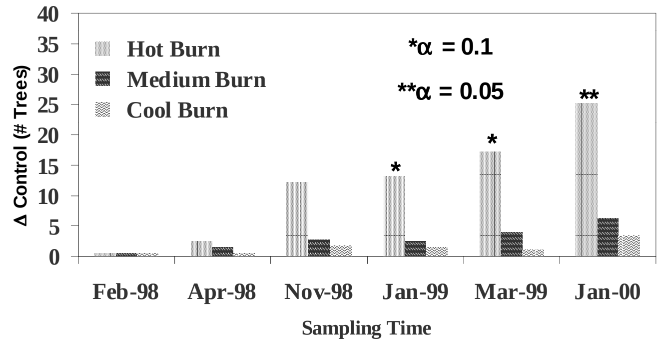

Figure 1b—Mean difference in number of crown symptom class three and four trees between burn treatments and unburned control. A detectable pattern in mortality began to emerge two years after the burn treatments were initiated.

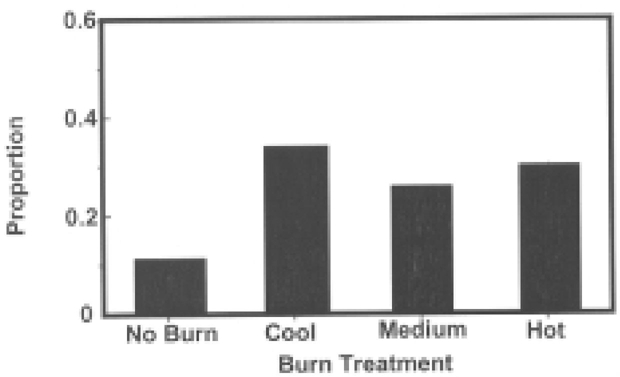

Figure 1c—Mean proportion of trees changing from less severe to more severe crown symptom classes in the three burn treatments and unburned control. All three burn temperatures had a higher proportion of trees with crown class changes than the unburned control.

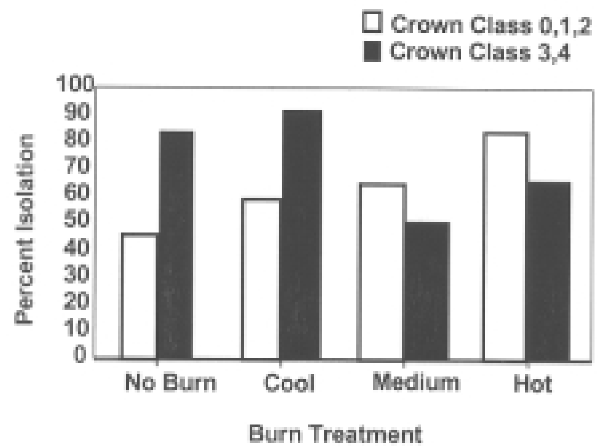

Figure 1d—Percent isolation of *Leptographium* species in woody longleaf pine roots relative to combined (less severe versus more severe) crown symptom classes. Isolation percent is based upon the presence of *Leptographium* species recovered within the total number of trees sampled.

of the three symptom classes used previously. In the present study, we define class 1 trees as those with crowns appearing as slightly off color, although green with less lustrous foliage compared to trees designated as class 0. The remaining three symptom classes are defined as previously reported (Otrosina and others 1999). Mortality and symptomatic trees were tagged and crown symptoms and d.b.h. were recorded.

Randomly selected symptomatic tree woody roots were excavated to approximately 0.5 meters from the root collar. About six root core samples were obtained along the exposed length with a 4-mm diameter increment hammer that penetrated about 2 cm into the xylem. Cores were immediately placed into small plastic bags and then into an ice chest for transport to the laboratory. Core samples were plated onto cycloheximide-amended and unamended 1.25 percent malt extract media, incubated, and evaluated as previously described (Otrosina and others 1999). Pure subcultures were obtained and fungal isolates were identified to genus or species.

Fungal isolates of Ophiostomatoid species obtained from root isolations were used in a pathogenicity study on randomly selected, healthy trees. Isolates of *Leptographium terebrantis, L. procerum, Ophiostoma minus* (used as a positive control), *Leptographium* sp. (resembling *L. serpens*), and an unidentified *Sporothrix* sp. were inoculated onto lower stems (1 m above root collar) and woody roots > 8-cm diameter. Stem bark was shaved to the outer phelloderm with a draw knife or similar blade to allow penetration of a 4-mm-diameter increment hammer to the cambium. Root and stem surfaces were sprayed with 95 percent ethanol prior to wounding. Agar cultures of the isolates were inoculated onto each tree stem and root via 4-mm-diameter agar plugs taken from culture margins. Outer bark retained in the bore of the increment hammer was replaced on the wound. Implements were thoroughly washed in 95 percent ethanol between isolates and inoculation points and each inoculation wound was taped with duct tape and marked for identification.

A stump infection survey was conducted for *Heterobasidion annosum* (Ha) by counting stumps within a 50-m radius circle of each plot center. Within each radial plot, total number of stumps over 10-cm diameter was counted and only those with visible fruiting bodies of Ha were defined as infected. Basidiocarps of Ha that were in good condition were transported to the laboratory for isolation and future study.

During May 2000, five trees from each of the five crown symptom classes were selected at random from hot burn treatment plots to determine stem cambial zone sucrolytic enzymes. A 6-cm by 15-cm section of bark was cut from the stem at breast height to expose cambial tissue. The cambium was scraped with a sharp razor blade and the scraped cambial tissue was then placed in small plastic bags. The bags were immediately submerged in liquid nitrogen contained in a Dewar flask, which served to store the flash frozen cambial tissue until transport to the laboratory for analysis. Analysis of sucrose synthase (SS), ATP-dependent phosphofructokinase (ATP-PFK), and Pyrophosphate-dependent phosphofructokinase (PPi-PFK) was described previously (Otrosina and others 1996).

Within each subplot, a randomly selected tree was used for fine root studies. Four times for each of two years, beginning three weeks after the last burn treatment, soil cores were obtained around the drip line of each selected tree by means of an inertial soil core sampler. Two core samples 6.25 cm in diameter were taken from two depths, 0 to 6 cm and 6 to 12 cm, at opposite positions around the tree. Cored positions were flagged to prevent repeat sampling. Fine roots (< 2-mm diameter) from within organic matter samples (0- to 6-cm depth) were separated from fine roots within mineral soil (6- to 12-cm depth) in the field by screening through a 5-mm mesh screen. Putative root-free soil was retained separately. All samples were placed in an ice chest for transport to the laboratory. Fine roots were oven-dried at 70°C for 24 hr and extracted for ergosterol analysis to estimate living fungal biomass. These procedures have been reported previously (Otrosina and others 1996; Sung and others 1995).

Also, samples of fine roots were taken from the sub-plot trees during March, June, and September of 1997, immediately placed in weak FAA (formalin:acetic acid:alcohol) solution, and were sectioned and stained according to protocols described previously (Walkinshaw and Otrosina 2002). Fine root anatomy was analyzed microscopically and variables such as size and number of starch grains, nuclear condition, tannin accumulation, and root mortality were measured.

Analysis of variance was conducted on tree mortality, crown data, fungal isolation, and fine root variables. The Chi-Square test and Dunnett's treatment versus control test were conducted on data relating to proportions of crown class changes over treatments during the 3-year study period.

Table 1—Proportion of roots in individual trees within the hot burn treatment exhibiting normal anatomy two to six months post burn[1]

	Soil Layer	
Tree	Organic	Mineral
	- - Proportion - -	
1	0.22	0.50
2	0.30	0.33
3	0.00	0.10
4	0.20	0.50
5	0.44	0.50
6	0.00	0.10
7	0.40	0.60
8	0.18	0.30
9	0.10	0.00
10	0.30	0.10

[1]Nine to 12 roots were sampled at random in the two soil layers

RESULTS

Post-Burn Observations

Temperatures from the thermometers placed in each treatment plot registered potentially lethal levels (approximately 130^0 to150^0 F.) in the hot burn treatments only. Spot checks of the duff layer revealed a large amount of decomposed organic matter containing fine roots on all treatments. The decomposed organic layer depth in the cool and medium burn treatment plots was indistinguishable from that of the control plots, indicating very little consumption of this organic matter fraction by the fire in these treatments. The hot burn plots had about one half the decomposed organic matter of the control plots (W.J. Otrosina, unpublished data).

Mortality and Root Infecting Fungi

After nearly three years post-treatment, mean cumulative mortality expressed as number of stems was highest in the hot temperature burn treatment (28.75 stems, $p = 0.06$) (figure 1a). The unburned control had the least mortality (5.5 stems) while the cool and medium treatments had mortality intermediate to the hot and control treatments with 11.25 and 9.5 stems, respectively. Numbers of trees with severe symptoms or mortality (crown class 3 or 4 trees) began to increase in the hot burn treatment with respect to the control plots at about two years post-treatment ($\alpha = 0.1$) (figure 1b), based upon Dunnett's treatment versus control test. At three years post-treatment, the number of trees in these symptom classes increased, exceeding control plot symptomatic tree counts by 25 trees ($\alpha = 0.05$). There were significant differences in proportion of trees that changed from less severe to more severe crown classes among all the burn treatments when compared to the control ($p = 0.039$, Chi-Square = 8.36, 3 df; figure 1c).

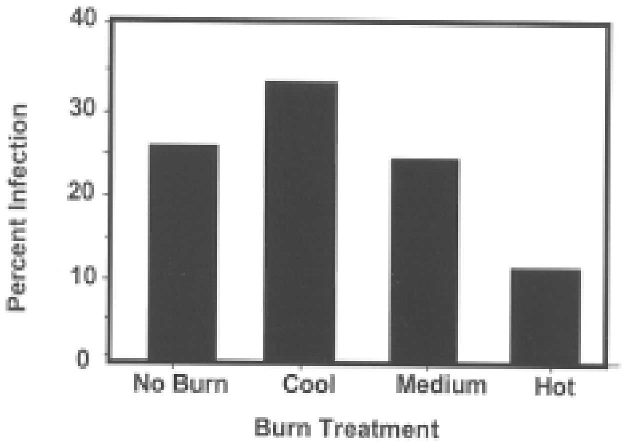

Figure 2—Mean percent of stumps with basidiocarps of *Heterobasidion annosum* within burn treatments. Note the lower percent of stumps with basidiocarps in the hot burn treatment.

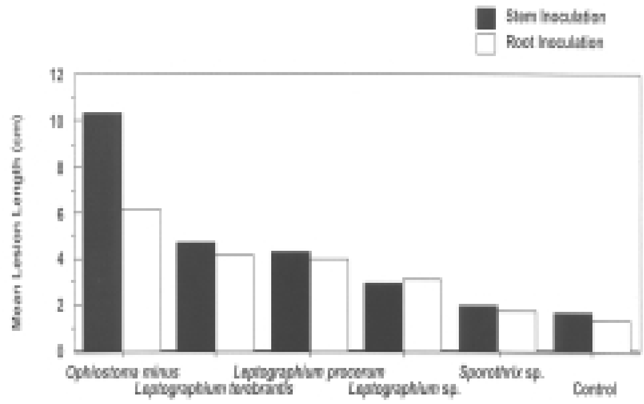

Figure 3—Mean lesion lengths in stems and roots of longleaf pine produced by inoculations with five Ophiostomatoid fungal isolates and a sterile control wound.

Isolations from woody root samples yielded several species of Ophiostomatoid fungi. Among the most common were *Leptographium terebrantis*, *Leptographium procerum*, and a *Sporothrix* sp. These comprised about 80 percent of the isolations from our root samples and no trends were observed in their relative frequencies with respect to burn treatments. The two *Leptographium* species we isolated were widespread throughout the study, regardless of treatment or crown class (figure 1d). On the other hand, *Sporothrix* sp. tended to be isolated more frequently in crown classes 0, 1, and 2.

Heterobasidion annosum Stump Infection

Viable Ha basidiocarps were observed in 7-year-old thinning stumps on our study sites. Eighty-five percent of the basidiocarps were found inside tangential splits in the sapwood caused by thinning equipment. These splits occurred within the outer 8 cm of the stumps and extended downward to the soil line. Infected stumps were widespread throughout the study site and all sampled plots yielded active basidiocarps. The percentage of stumps with active basidiocarps ranged from 7 percent to 51 percent over all treatments. The hot burn treatment had a mean proportion of 0.13 infected stumps, less than the control, cool, and medium burn treatments ((figure 2) ($p = 0.1$)).

Stem and root inoculations

Significant differences in cambial zone lesion length ($\alpha = 0.05$) were found among the fungal isolates tested for pathogenicity (figure 3). *Ophiostoma minus* produced the longest lesions, followed by *L. terebrantis* and *L. procerum*. An unidentified *Leptographium* species, resembling *L. serpens*, also produced a lesion that was significantly longer than the control wound. The lesion produced by an unidentified *Sporothrix* species was slightly longer than the control wound but statistically indistinguishable from it. Roots tended to have significantly smaller lesion lengths than stem inoculations overall ($\alpha = 0.05$).

Stem cambial zone sucrolytic enzymes

Regressions of enzyme specific activities with respect to the five symptom severity classes as independent variables for SS, PPi-PFK, and ATP-PFK indicated decreasing enzyme activities associated with increasing symptom severity (SS = $-26.5Z + 133$, PPi-PFK = $-30.3Z + 157.8$, and ATP-PFK = $-10.7Z + 68.7$; $p = 0.0001$, $R^2 = 0.53$, 0.42, and 0.44, respectively).

Fungal Biomass Estimates

Ergosterol analysis to estimate live fungal biomass indicated a higher concentration in the soil organic layer root clumps (figure 4) when compared to the other three soil fractions. These organic matter root clumps ranged from 16 to 49 µg/g ergosterol (dry weight basis). Also, these values were consistent over the two-year sampling period. In contrast, root-free soil had the least ergosterol over all sampling intervals. Root clumps in the soil and root free organic matter had intermediate amounts of ergosterol (range 5-15 µg/g dry weight). We did not detect clear treatment effects with respect to ergosterol concentration, although overall values in burn plots tended to be higher in the first year post-treatment than in the second year.

Fine-Root Anatomy and Mortality

Proportion of roots in the hot burn exhibiting normal anatomy two to six months post-treatment is given in table 1. The organic layer root mortality ranged from 56 percent to 100 percent. Root samples collected from the mineral layer had 40 percent to 100 percent mortality. No significant differences were found for root mortality between the two soil fractions, nor was fine root diameter or starch content related to mortality ($r^2 = 0.09$ and $r^2 = 0.30$, respectively). On the other hand, histological analysis of roots from mineral soil indicate a significant relationship between number of cortical cell starch grains and root mortality for the control and cool burn treatments ($r^2 = 0.73$ and 0.75, respectively) (figure 5). We found no relationship between number of cortical cell starch grains and root mortality in the medium and hot burn treatment ($r^2 = 0.02$ and 0.05, respectively).

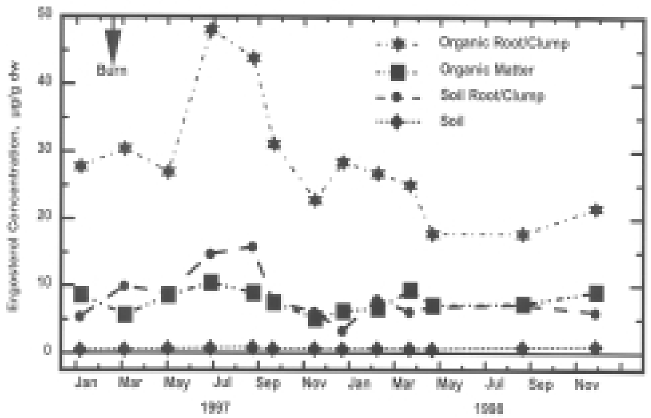

Figure 4—Below-ground distribution of live fungal biomass expressed as mean ergosterol concentrations in four soil or organic matter fractions. Sampling was done periodically over 18 months after beginning of the burn treatments. Symbols represent ergosterol concentrations of a given soil fraction at the specific sample date.

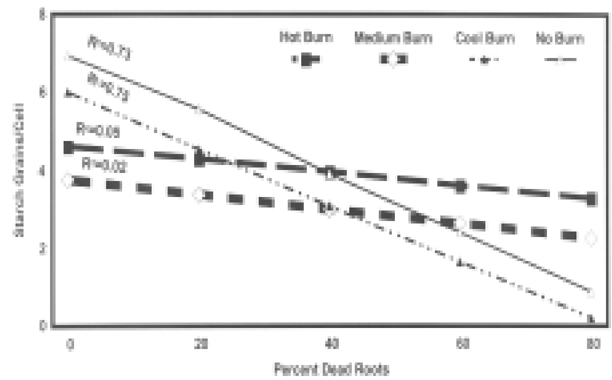

Figure 5—Regression relationship between root death and number of starch grains in fine root cortical cells. An inverse relationship exists between number of starch grains and percent dead roots in the hot and medium burn treatments. No relationship between root death and starch grains was detected in the cool burn and control treatments.

Dead roots often retained their bark cells in tight multicellular layers that resisted tearing when sectioned. When viewed macroscopically, these roots were often confused with undamaged, live ones. Sectioning and staining these roots revealed extensive internal damage. Large numbers of starch grains were trapped within necrotic cells, the cambium was disorganized, and nuclei stained abnormally. Bark formation and persistence of roots in burned plots was normal, as active formation of bark cells occurred in 64 percent of roots from burned plots and 58 percent of roots from unburned plots. Excess tannin accumulated in 65 percent of the roots from the burn plots and in only 12 percent of those from the unburned plots. Hydrolysis of cortical cell contents was limited in the burn plot samples and starch grains were intact. Cell wall structure, the cambium, and nuclei appeared to be preserved by released tannin.

DISCUSSION

The trend toward increasing mortality over time is evident in the hot burn treatment. Mortality onset is delayed in the burn treatments for at least two years, based upon our data (figure 1a). By the third year, clear separation between the hot burn treatment and unburned control plots, and the other burn treatments, is evident. Even the cooler burn treatments, while having less mortality, tended to have more trees progress from less severe to more severe crown symptoms when compared to the control (figure 1b). Thus, mortality cannot be ascribed to direct heat effects such as cambial scorching. Further evidence for indirect effects of the hot burn is the onset of decline symptoms that precede mortality, suggesting physiological and pathological causes. Regarding the physiological basis for the decline syndrome, analysis of SS activity is a quantitative indicator of tree stress (Sung and others 1993, Otrosina and others 1996) and corresponds well to the crown symptom classification we established. This suggests our visual crown evaluations approximate tree physiological status as defined by SS activity.

The mechanism driving this decline and mortality appears very complex. In this study, the term “hot burn” is relative and must be taken in context. In the hot burn treatment, about one half the amount of post-burn, decomposed organic matter containing fine roots still remained. This fact may provide clues toward understanding the mechanism as to why such mortality is triggered by fire. One hypothesis is that infrequent prescribed fire intervals allowed buildup of this decomposed organic matter containing fine roots. These roots are then susceptible to indirect heat effects. Our data on root anatomy show that fine roots can be damaged by heat without being consumed and without showing obvious macroscopic damage. Cortical cell starch grains were intact and their numbers were not associated with root mortality in the hot and medium burn treatment (figure 5). In dead fine roots, we observed limited hydrolysis of cortical cell contents, intact cell wall structure, and abundant intact achromatic nuclei in these burn plot samples, presenting further evidence of rapid cell death as would occur under a lethal pulse of heat. In contrast, there is an inverse relationship between numbers of cortical cell starch grains and root mortality in the mineral soil of the unburned and cool burn treatments (figure 5), indicating a relatively slower physiological process taking place in fine roots where their exposure to high temperatures is limited (Walkinshaw and Otrosina 1999). On the other hand, root death due to direct heat effects in mineral soil is somewhat enigmatic. Soil does not conduct heat efficiently, although steam can conceivably penetrate short distances through soil pores. We observed some interconnections between finer roots in the organic layers and the mineral soil and thus, damage to roots above may effectively cutoff roots in lower soil layers. Also, damage to larger woody lateral roots near the surface can affect more distal fine roots.

We found the highest portion of living fungal biomass in the fine root clumps of the organic layer (figure 4). Because the organic layer fine root clumps are presumed largely comprised of ectomycorrhizal fungi, and some studies indicate fine root production and associated symbiotic fungal biomass may account for two-thirds of the annual biomass production in some forest types (Marshall and Waring 1985), heat damage to this root fraction can result in significant stress.

Another element driving mortality may be facultatively pathogenic fungi. We found Ophiostomatoid species such as *Leptographium terebrantis*, *L. procerum*, and *Sporothrix* sp. to be widespread in woody roots regardless of treatment or crown condition (figure 1d). Because these fungi are adapted to insect dissemination, and little is known about the root feeding bark beetle species that are involved in their spread, critical interactions between insects and these fungi probably occur. Other studies have associated these fungi with insect attack, mortality, or decline symptoms in loblolly pine and longleaf pine stands (Otrosina and others 1997, Otrosina and others 1999). Longleaf pine are generally regarded as resistant or highly tolerant to root disease fungi and reports of Ophiostomatoid fungi attacking woody roots of longleaf pine, other than Otrosina and others (1999), are few. In our inoculation experiment, we demonstrated pathogenicity of these Ophiostomatoid species (figure 3) on longleaf pine and thus established their association with observed decline symptoms. The fact that Ophiostomatoid fungi are widespread begs the question as to their specific role. We recovered these fungi from both asymptomatic trees and declining trees regardless of treatment or crown condition. In asymptomatic trees, we isolated *L. terebrantis*, *L. procerum,* and unidentified *Leptographium* and *Sporothrix* species from both symptomatic roots and roots exhibiting no resinosis or staining, although symptomatic trees tended to have more resinous roots than non-symptomatic trees. Resinous lesions in roots signify an active defense by the tree against the pathogen, diverting energy resources to the infection site. If under stress, this can result in significant loss of growth and maintenance functions and may account for decline symptoms. *L. procerum* can survive in pine woody tissues for some time without causing obvious symptoms (Horner and others 1987) and Bannwart (unpublished MS thesis, University of Georgia Department of Plant Pathology 1998) found that *L. procerum* and *L. terebrantis* can survive in callused stem lesions of longleaf pine seedlings. Also, evidence suggesting the presence of *L. terebrantis*, *L. procerum*, and other Ophiostomatoid species in roots is a stress indicator in longleaf pine and loblolly pine stands has been presented (Otrosina and others, 1997, Otrosina and others 1999). Thus, the occurrence of root infecting *Leptographium* species may contribute to the decline syndrome after an additional stressor, such as fire damaged fine roots, is introduced in an already stressed system. Given these biological circumstances, fungi that are not regarded as pathologically important can cause significant and unexpected damage.

Other root pathogens such as Ha have not been regarded as important in longleaf pine because of its tolerance or resistance to this pathogen. We found the fungus to be widespread in our study, judging by stump infection (figure 2) and by observations of trees infected by Ha throughout our study. The pathogen was an important factor in longleaf pine decline in another area on the Savannah River Site (Otrosina and others 1999). Because Ha infection in longleaf pine is not often reported as a problem, infected trees we observed in this study may be another sign of complex pathological interactions involved. Infected stumps in our study continued to produce basidiocarps at least seven years after the last thinning, although stumps in the hot burn plots had produced less basidiocarps than stumps from all other treatments. Unlike Ophiostomatoid fungi, Ha decomposes woody root tissues and can persist for long periods of time in infected stumps and roots because it is highly adapted to resinous wood (Otrosina and Cobb 1989). Longleaf pine stumps are highly resinous and resist decomposition for a long period of time. When healthy tree root systems contact colonized stump roots or roots from infected living trees, the fungus spreads from tree to tree causing mortality and downed trees from disintegration of structural roots. Once present in a stand, this fungus can become a recalcitrant problem. We found infected stumps as small as 12 cm in diameter, demonstrating the importance of applying borax formulations to freshly cut stump surfaces to prevent infection from airborne Ha basidiospores.

The longleaf pine decline associated with prescribed burning on this study site cannot be attributed to a specific cause. We described a complex of interacting factors implicating fire intensity, fine root damage, *H.* annosum, Ophiostomatoid fungi, and physiological dysfunction. Soil type and stand density are also important components involved in this syndrome that require investigation. Certainly, fire dependent ecosystems should be regarded as exotic ecosystems (Otrosina 1998) when fire reintroduction after a long period of fire suppression is contemplated. Under these circumstances, fire reintroduction must be conducted with caution and consideration must be given to below ground pathological and physiological processes.

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ASSESSMENT OF LOBLOLLY PINE DECLINE IN CENTRAL ALABAMA

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Abstract—Loblolly pine (*Pinus taeda* L.) decline has been prevalent on upland sites of central Alabama since the 1960's. The purpose of this study was to compare Forest Health Monitoring (FHM) standards and protocols with root health evaluations relative to crown, stem, and site measurements. Thirty-nine 1/6 acre plots were established on loblolly decline sites in nine central Alabama counties. Sites were selected on federal, state, and private industrial lands to measure variables of decline symptoms, age classes and management procedures. A two-root sampling procedure, selective media, and soil baiting assay methods were used to isolate pathogenic root infecting fungi. Pitfall traps collected root-feeding insects from which *Leptographium* species were recovered. FHM indicators of tree crown conditions were recorded on all pines in the plots. Preliminary results showed a significant correlation between live crown ratio and incidence of *Leptographium* spp. We recovered *Leptographium* from damaged roots in eighty-four percent of plots. The pine basal area was significantly reduced with increased incidence of *Phytophthora cinnamomi* Rands, with *P. cinnamomi* being recovered from the soil root zone in 50 percent of the plots. Histological examination of root damage indicated a significant correlation between reduced growth and root wounding.

INTRODUCTION

A decline of loblolly pine, *Pinus taeda* L., has been observed on the Talladega National Forest in central Alabama since 1959 (Brown and McDowell 1968). The decline condition was initially referred to as "loblolly pine die-off," and was most frequent in sawtimber-size trees over age 50. During the 1960's and 1970's, studies were initiated to determine the cause of the die-off and the rate of spread. Twenty-four plots were established in loblolly pine stands on the Oakmulgee District to assess decline and mortality. Soil and root samples were analyzed for the presence of root pathogens including *Phytophthora cinnamomi* Rands, a primary factor in the development of littleleaf disease. There was some recovery of *P. cinnamomi* from the decline plots, but it was reported that root system deterioration of the die-off trees was more extensive than that found in littleleaf diseased trees (Brown and McDowell 1968). Although a specific cause was not determined, several observations and conclusions came out of this study. Lateral root deterioration preceded the presence of observable foliage symptoms. Symptoms included sparse crowns, chlorotic needles, reduced radial growth at age 40-50, and heavy cone crops occurring prior to mortality. Mortality occurred 2 to 6 years after onset of symptoms. Also, a large percentage of the fine roots died before tree mortality occurred (Brown and McDowell 1968).

The decline symptoms were most severe on the Oakmulgee Ranger District near Centreville, AL, which falls within the Upper Gulf Coastal Plain Province. During the 1940's and 1950's, other surveys in the Upper Coastal Plain reported damage to shortleaf pine (*Pinus echinata* Mill.) stands caused by littleleaf disease. This disease was strongly associated with *P. cinnamomi* on sites with low fertility and poor internal drainage (Campbell and Copeland 1954, Roth 1954). Loblolly pine was also affected by littleleaf disease when associated with diseased shortleaf pine sites (Campbell and Copeland 1954).

The forests of the Oakmulgee were predominately longleaf pine (*Pinus palustris* Mill.) during the pioneer settlement era of the early 1800's. From 1908 until 1929, most of these trees were harvested for lumber, and the land was converted to agricultural use. During the 1930's and 1940's, federal acquisition programs relocated farm families and established National Forests (Johnson 1947). Abandoned farmland then regenerated to loblolly pine and shortleaf pine.

Management recommendations from the 1960's and 1970's for the Oakmulgee Ranger District were to prevent decline situations by reducing the rotation age of loblolly pine stands from 70 to 60 years and by maintaining basal area at 60 to 70 ft² per acre. Recommendations also

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Table 1—Number of plots by location, physiographic region, and land management ownership

Number of Plots	Soil Physiographic Regions Of Alabama	County	Land Management Ownership
9	Piedmont	Clay, Cleburne, Talladega	Talladega National Forest (Federal)
5	Ridge & Valley	Calhoun	Choccolocco State Park (State)
16	Coastal Plain	Bibb, Hale, Chilton, Perry	Talladega National Forest (Federal) (Oakmulgee R.D.)
9	Cumberland Plateau	Tuscaloosa	Gulf State Paper Corporation (Private-Industrial)

included the conversion of declining loblolly pine stands to longleaf pine. To date, approximately 20,000 acres have been converted to this species. However, there are still about 40,000 acres of loblolly stands on the Oakmulgee District in various stages of decline. A recent biological evaluation of decline sites on this District found that *P. cinnamomi* and *Pythium* sp. are predominant pathogens associated with loblolly pine fine root deterioration (Hess and others 1999).

Other areas of central Alabama have reported loblolly decline, including National Forest lands in the Anniston/Heflin area of Alabama (Hess 1997). Forest industry land managers reported declining loblolly stands in Tuscaloosa and Bibb Counties (Allen 1994). Loblolly pine decline on littleleaf diseased sites on two National Forests within the Piedmont Physiographic Region of South Carolina has been found (Oak and Tainter 1988). In addition, loblolly pine decline associated with *P. cinnamomi* and *Pythium* species was also reported in Louisiana (Lorio 1966).

Since its inception in 1990, Alabama has participated in the USDA Forest Service's Forest Health Monitoring (FHM) Program. A main objective of this program is to develop and implement standards and protocols for assessing conditions of forest resources. Preliminary analyses of FHM (P3) plots and other survey data collected in Alabama and other southern states from 1995 through 1997 identified 30 percent of loblolly pine stands as having decline symptoms (Steinman and others 2000). This FHM Evaluation Monitoring Project represents further investigation of causal agents associated with the decline of loblolly pine within central Alabama. The purpose of this study was to compare the presence of pathogens in roots and soil with tree growth and FHM indicators on loblolly pine decline sites.

METHODS

Plot Description

Sites for plot establishment were selected on federal, state, and private industrial lands. Thirty-nine 1/6 acre sample locations in nine central Alabama counties were selected in the spring of 2000. Plot establishment followed the FHM guidelines (Dunn 1999), using a cluster of four 1/24 subplots. The plot locations fell within four Physiographic Regions of Alabama: the Piedmont, Ridge and Valley, Upper Coastal Plain, and Cumberland Plateau (table 1). At each location, root health assessment was accomplished by selecting three dominant, or co-dominant, symptomatic pines nearest the plot center of the center subplot. Root sampling was done with the modified two-root excavation method (Otrosina and others 1997).

Radial growth was measured by obtaining an increment borer core at breast height (BH) of each of the sample trees. With the aid of hand lenses, increment cores were measured for five and ten year radial growth increments and age.

FHM Indicators of Tree Crown Conditions

Tree crown conditions were measured on all pine trees (DBH ³ 5.0) within all 39 plots. The crown measurements included live crown ratio, crown light exposure, crown density, crown dieback, and foliage transparency. Live crown ratio is a measure of crown length and its relationship to total tree height. Crown light exposure and crown position are combined in analysis to determine stand and canopy structure. Once the live crown ratio, crown light exposure, and crown position are determined, the next step is to measure how much of a crown exists. Crown density, which includes foliage, branches and reproductive structures, measures the crown biomass. Crown dieback defines how much of the crown does not have foliage but has fine twigs, indicating a loss of vigor or growth potential. Foliage transparency estimates how dense the foliage is on branches, indicating a loss of vigor or stress due to foliage damage or defoliation (USDA Forest Service 2000).

Insect Interactions

Pitfall traps were installed on 15 of the 39 plots, and insects collected weekly from April 17th to June 5th, 2000. Traps were constructed of 20 cm lengths of 10 cm

Table 2—Sample plot means of tree measurements by types of forest ownership

Measurements	Public (n = 30 plots) Mean	S.E.	Industry (n = 9 plots) Mean	S.E.	Probability
All overstory pine trees					
Stand age (years)	46	2	36	2	0.0265
Total pine basal area (ft²/acre)	69.3	3.4	63.3	7.1	0.41
DBH (inches)	10.0	0.3	10.2	0.5	0.76
Live crown ratio (pct)	38	1	41	1	0.17
Foliage transparency (pct)	32	0	29	1	0.00
Crown dieback (pct)	1	0	0	0	0.67
Crown density (pct)	39	1	40	2	0.70
Plot sample trees					
DBH (inches)	11.4	0.5	11.0	0.7	0.67
Last 5-yr basal area increment (ft²)	0.09	0.01	0.11	0.02	0.18
Last 10-yr basal area increment	0.18	0.02	0.20	0.02	0.42
Live crown ratio (pct)	37	1	41	2	0.10
Foliage transparency (pct)	31	1	29	1	0.05
Crown dieback (pct)	1	0	0	0	0.71
Crown density (pct)	39	1	39	1	0.85

diameter drainpipe with eight entrance holes spaced around the pipe. The interior of each trap was coated with liquid Teflonä to prevent insect escape. Ends were capped with plastic lids and two holes were drilled in the bottom end for drainage. Traps were placed so that the entrance holes were slightly above ground level. Each trap was baited with two 8 ml glass vials, one containing 95 percent alcohol and one containing turpentine. Two freshly cut pine stems were also placed inside the traps (Klepzig and others 1991). Trapped insects were placed in sterile polyethylene specimen cups and maintained for two to three days at 4°C until isolations could be made. Insects were inventoried and rolled across cycloheximide-streptomycin amended malt extract agar (CSMA—2 percent MEA containing 800 ug/ml of cycloheximide and 200 ug/ml of streptomycin sulfate) and unamended malt extract agar (MEA) (Hicks and others 1980). Agar plates were incubated at 25°C and colonies resembling *Leptographium* were transferred to sterile plates or slants of MEA.

Processing Roots

Two primary roots from each sample tree were excavated using hand tools, beginning at the root collar and extending out to the tree drip line. The primary roots were then cut from the tree and removed. All soil samples were collected adjacent to the roots.

Root samples were collected during April, May, and June of 2000. The fine roots from each primary root were excised, bagged, labeled and maintained in the field on ice. The

Table 3—Correlations between crown vigor associated with plot sample trees

	Crown dieback (pct)	Crown Density (pct)	Foilage Transparency (pct)	Live Crown Ratio (pct)	BAI[1] Last 5 years (ft²/tree)	BAI Last 10 years (ft²/tree)
	- - - - - - - - Pearson correlation coefficient - - - - - - - -					
	- - - - - - - Probability of significance - - - - - - -					
BAI last 5 years	-0.15	0.38	-0.20	0.54		
(ft²/tree)	0.36	0.02	0.21	0.00		
BAI last 10 years	-0.23	0.43	-0.10	0.49		
(ft²/tree)	0.15	0.01	0.52	0.00		
Pine basal area	-0.10	-0.15	-0.19	-0.04	-0.27	-0.24
(ft²/acre)	0.55	0.35	0.25	0.79	0.09	0.13
Stand basal area	-0.06	-0.14	-0.02	-0.11	-0.25	-0.19
(ft²/acre)	0.71	0.40	0.88	0.50	0.13	0.26

[1] BAI = basal area increment

Table 4—Sample plot means of tree measures of vigor by incidence of *Leptographium* spp

Measurements	Incidence of *Leptographium* in roots or soil 0 pct (n = 4 plots) Mean	S.E.	33 pct (n = 8 plots) Mean	S.E.	67 pct (n = 16 plots) Mean	S.E.	100 pct (n = 11 plots) Mean	S.E.	F Probability
Total pine basal area (ft²/acre)	73	16	70	7	63	3	73	6	0.52
Last 5-yr basal area increment (ft²)	0.11	0.04	0.10	0.01	0.09	0.01	0.07	0.01	0.32
Last 10-yr basal area increment (ft²)	0.20	0.05	0.20	0.02	0.20	0.02	0.15	0.02	0.34
DBH (inches)	12.4	1.9	11.1	0.7	11.2	0.6	11.4	1.0	0.86
Crown dieback (pct)	1	1	0	0	0	0	1	1	0.14
Crown density (pct)	38	2	41	2	41	1	37	2	0.24
Foliage transparency (pct)	29	1	29	1	32	1	30	1	0.14
Live crown ratio (pct)	42	3	42	2	37	2	35	1	0.06

primary roots were also randomly chipped or cut into pieces, bagged, labeled, and iced for transportation to the laboratory. Roots were excavated from 117 trees, with 234 primary roots sampled, along with collections of fine roots and soil samples from the root zones. Root samples for isolation of fungi from primary and fine roots were transported to Louisiana State University, Plant Pathology Laboratory, Baton Rouge, LA.

Isolation of Microorganisms

Phytophthora spp. and *Pythium* spp. were isolated from fine roots and soils using three methods. The first method used the selective medium PARP(H) (Ferguson and Jeffers 1999). Eight to ten pieces of fine roots (< 2mm diameter) were washed, dried, cut into 2 cm lengths, and plated on PARP(H). The specimens were incubated in the dark at 20°-25°C for 3 days. Subcultures were established from *Phytophthora*-like fungi growing from the roots. The second method of isolating was soil assay. Soil samples were assayed from a soil suspension on PARP(H) (Jeffers 2000). The plates were examined for *P. cinnamomi* after incubation for 48 to 72 hours in the dark. A third isolation method employed for *Phytophthora* and *Pythium* species was baiting. Soil samples collected during root excavation were incubated in Petri plates with fresh camellia, juniper, or pine stems (Jeffers 2000). Plates were incubated at 24 and 72 hours, after which we checked for characteristic *Pythium* or *Phytophthora* sporangia.

Isolation of Ophiostomatoid fungi from primary roots utilized selective media. Roots were cut into small pieces, rinsed in tap water, decontaminated in 10 percent commercial bleach, treated with 10 percent ethanol solution for one minute, rinsed again in tap water for three minutes, and blotted dry. Four pieces were placed in a Petri plate containing selective medium (CSMA) to isolate *Leptographium* species. Plates were incubated at 25°C and *Leptographium* isolates were subcultured from hyphal tips and conidial heads onto MEA. Subcultures were maintained in MEA slants and stored at 8°C until identified.

Table 5—Sample plot means of tree measures of vigor by incidence of *P. cinnamomi*

Measurements	-----Incidence of *P. cinnamomi* in roots or soil----- 0 pct (n = 19 plots) Mean	S.E.	33 pct (n = 12 plots) Mean	S.E.	67 pct (n = 5 plots) Mean	S.E.	100 pct (n = 3 plots) Mean	S.E.	F Probability
Total pine basal area (ft²/acre)	80	4	55	4	56	5	63	9	0.00
Last 5-yr basal area increment (ft²)	0.09	0.01	0.10	0.02	0.08	0.01	0.11	0.04	0.70
Last 10-yr basal area increment (ft²)	0.18	0.02	0.19	0.03	0.18	0.01	0.20	0.07	0.96
DBH (inches)	11.8	0.6	11.1	0.8	10.5	0.7	11.3	2.1	0.8
Crown dieback (pct)	0	0	1	0	0	0	1	1	0.77
Crown density (pct)	39	1	39	2	39	4	41	2	0.95
Foliage transparency (pct)	30	1	31	1	33	2	30	3	0.55
Live crown ratio (pct)	38	1	38	2	39	2	34	6	0.72

Soil samples were analyzed for *Leptographium* sp. by removing a 10 g aliquot from thoroughly mixed soil previously collected near lateral roots. Root fragments were removed from the aliquot by sieving and suspending them in 40 mls of sterile, 0.5 percent water agar. One milliliter of this suspension was pipetted into ten petri dishes containing 10 mls of CSMA. Dishes were incubated at 25°C and examined daily for the presence of fungus. Isolates were transferred to MEA slants and stored at 8°C until they could be identified.

Root Damage Assessment

During the root excavation and sampling procedures, a sub-sample of 17 plots was chosen to evaluate fine root damage through histological examination. Random samples of unwashed fine roots were taken from the primary roots and placed in formalin/acetic acid/alcohol fixative (FAA) for 14 days (Sass 1951). Fixed root specimens were cut to 1 to 3 mm, dehydrated in an alcohol series, embedded in paraffin, and sliced into 7 to 10 µm transverse sections. Slides were stained with a variety of schedules, including Papanicolaou's hemotoxylin-eosin or an acid-Schiff procedure (Hass 1980, Horobin and Bancroff 1998). Stained sections where observed under a light microscope and then catalogued into damage categories (Walkinshaw and Tiarks 1997, Walkinshaw and others, 2001).

Data Analysis

Measures of stand structure, tree growth, and tree crown and damage conditions were used to summarize decline symptoms of loblolly pine for each plot. Values were compared between the 30 plots located on public land and the 9 plots on industrial ownership to determine if the presence of decline symptoms was related to different types of forest management these ownerships represent. Data were analyzed using T-tests.

Correlations between continuously scaled measurements of stand structure, crown conditions, radial growth, and root conditions were also calculated. These summaries were used to interpret physiological and pathological relationships among different indicators that express decline symptoms. We used the percentage of the three sample trees on each plot with pathogens present to define four categorical levels of pathogen incidence (0, 33, 67, or 100 percent). We then compared plot values for stand structure, tree growth, and tree crown conditions among the categories of pathogen incidence by analyses of variance.

Proportions of damaged roots, root mortality, and number of starch grains in cortical cells were recorded from histological examinations and paired with tree growth and crown variables. Correlations and regression analysis were conducted on these data (Walkinshaw and Otrosina 2001).

RESULTS

Analysis of tree crown condition indicators of the 39 sample plots, compared to the other loblolly pine Forest Health Monitoring plots, shows a difference in transparency of the tree crowns. Transparency (the amount of light filtering through the foliated portion of the tree crown) was considerably greater for our sample plots, as would be expected, as crowns decline and become sparse. Foliage transparency was greater on public land (table 2). Stand age on public land was ten years older than that of industrial land. Tree crown condition indicators showed a significant correlation between DBH growth, crown density, and live crown ratio (table 3). Live crown ratio was less on plots having a greater incidence of *Leptographium* sp. (table 4). On a plot basis, the incidence of *Leptographium* sp. from roots of the 39 sample plots was 84 percent from roots, and 33 percent from soils. Overall *Leptographium* isolation percentage was greater on public lands (93 percent) when compared to industrial lands (55 percent).

Using baiting procedures, *Phytophthora cinnamomi* was isolated from soils in 50 percent of the plots on public land and slightly higher on industrial land (55 percent). *P. cinnamomi* was not recovered from root isolations. Plots with *P. cinnamomi* had less pine basal area than those those plots where *P. cinnamomi* was not found by soil baiting (table 5).

Microscopic examination of 700 fine root pieces from the 17 selected plots showed high incidence of root injury and mortality. The number of starch grains in the cortical cells was reduced and the disposition of tannin was excessive (Walkinshaw and others 2001). The inverse relationship between proportion of roots with injuries and radial growth of the cambium in the last 5 years was significant ($r^2 > 0.50$). Damage to resin canals was also a useful variable in the interpretation of microscopic data (Walkinshaw and others 2001) and was consistent with the observed root pathological status.

DISCUSSION AND CONCLUSIONS

The majority of the plots in this study had trees with decline symptoms, and assessment of woody roots, fine roots, and soil demonstrated the presence of root pathogenic fungi. The results of this assessment are consistent with the observations of Brown and McDowell (1968) who characterized fine root deterioration in 40 to 50 year-old trees prior to the onset of severe decline symptoms. A notable difference between their study and ours lies in the recovery of pathogenic root infecting fungi. Isolation and detection procedures for Pythiaceous and Ophiostomatoid fungi from roots and soil have become more efficient since the Oakmulgee studies of the 60's and 70's (Tainter and Baker 1996). Even though the edaphic parameters of this assessment are not complete, the abundant recovery of *Leptographium* sp. and *P. cinnamomi* from primary woody and fine roots, respectively, and the associated soils, coupled with the ability to evaluate the crown symptoms with established FHM protocols, help to further define the components of loblolly pine decline. *Leptographium* species are associated with pine decline and mortality in connection with root-feeding beetles and weevils that attack living trees (Harrington and Wingfield 1977, Otrosina and others 1997). Hess and others (1999) concluded that *P. cinnamomi* and *Pythium* sp. appeared to be the primary pathogens associated with the deterioration of loblolly pine fine root systems on the Oakmulgee. Although *P. cinnamomi* is considered a primary pathogen causing littleleaf disease, other factors such as poor soil aeration, low fertility, periodic moisture stress, and other soil-inhabiting microorganisms are also damaging to fine roots (Oak and Tainter 1988). Loblolly pine, although affected by littleleaf disease, is considered less susceptible and was planted to replace shortleaf pine on sites within the historic range of littleleaf disease (Oak and Tainter 1988, Campbell and Copeland 1954). Littleleaf disease of loblolly pine generally has been reported on eroded Piedmont soils. This is in contrast to the somewhat deeper soil profiles we encountered in our initial soil examinations prior to this study. However, our data suggest decisions to plant loblolly pine on sites with similar characteristics and in similar physiographic areas should be approached with caution, especially if planning rotation ages greater than 35-40 years.

This assessment of loblolly decline included plots in four Physiographic Regions, encompassing a zone in central Alabama from the east (Cleburne and Clay counties) to the west (Tuscaloosa and Hale counties). The evaluation of site variables, including soil classification, bulk density, soil porosity and moisture capacity, and soil nutrient analysis will be a key to assessing the influence of soil and root pathogens recovered from these sites and their relationship to crown characteristics of symptomatic loblolly pines. The soil and site measurements will not be completed until late 2001, at which time a complete evaluation and analysis of all data, including site, root, soil, tree growth, crown indicators, and crown damage will be accomplished. The results of this preliminary study indicate: (1) Management on public lands shows that damage and mortality increases with age of the stands, especially after age 40. (2) Loblolly pine decline symptoms are the same as littleleaf disease of shortleaf pine, and preliminary results of our evaluation show a correlation between reduced radial growth and BA, declining crowns, root damage, and recovery of *P. cinnamomi* and *Leptographium* sp. (3) Loblolly decline is prevalent on sites within the historic range of littleleaf disease and is associated with sites and soils other than the heavy clay soils of the Piedmont Province.

Evaluation of loblolly pine decline in central Alabama is ongoing. The goal is to define the parameters of decline sites, develop a predictive risk model, and estimate amount of land affected. The evaluation of edaphic factors is continuing with soil classification, bulk density analyses, and soil porosity analyses in progress. Soil sample collections for nutrient analysis are scheduled for the summer of 2001. These soil variables will then be incorporated into an overall analysis linking management regimes, root pathological assessments, and root feeding insects, which will further define biological foundations of FHM protocols.

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COTTONWOOD FIBER FARM PEST MANAGEMENT: COTTONWOOD LEAF BEETLE

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Abstract—Defoliation by the cottonwood leaf beetle, CLB, (*Chrysomela scripta* F.) can pose a significant threat to the growth and development of one and two-year old Populus plantings. In the southeastern United States, guidelines for monitoring CLB populations at the landscape level have not been fully developed. Accurate determination of when CLB are present in the field could greatly aid in the efficient management of this pest. To address this situation, we compiled data regarding the developmental rate of the CLB to test predictive models of CLB development. Based upon comparisons with field observations, current temperature-dependent growth models hold promise for predicting the occurrence of first generation adult CLB in the field. Prediction of the appearance of specific CLB life stages, especially in subsequent generations, may be somewhat more difficult and requires more examination.

INTRODUCTION

The cottonwood leaf beetle, CLB, (*Chrysomela scripta* F.) is one of the most important economic pests of *Populus* in the United States (Burkot and Benjamin 1979; Drooz 1985). The CLB is a defoliator, with larval and adult stages feeding on the young leaves and shoots of *Populus* clones (Harrell and others 1982). The defoliation that results from CLB feeding activity poses the most threat to one and two-year old plantings, potentially hampering growth and the accumulation of biomass (Calbeck and others 1987; Fang and Hart 2000; Reichenbacker and others 1996). Accurate determination of when CLB are present in the field could greatly aid in the efficient management of this defoliator.

Cottonwood leaf beetles overwinter as adults in leaf litter and under bark, emerging as temperatures rise in the spring (Head 1972). Shortly after emerging, adults mate and females begin to oviposit on the leaves of *Populus* and other suitable hosts. As for most insects, emergence and development of these offspring from egg to adult is closely tied to temperature. To correctly predict emergence dates or developmental time as a function of temperature, the time scale should be represented as physiological time. This physiological time scale is a combination of calendar time and temperature (Mizell and Nebeker 1978). Theoretically, the rate at which heat is accumulated during the spring will determine when specific life stages are expected to be present. Prediction of when CLB adults are apt to first appear in the field would be of benefit to growers in implementing various management tactics.

Insects are known to require a certain amount of heat to develop from one stage to the next (Gilbert and Raworth 1996). This heat requirement is constant and therefore can be used to predict the occurrence of life stages (larvae, pupae, adults) in the field. Temperature-dependent growth models are predictive tools constructed from developmental studies conducted on specific insect species at a series of constant temperatures. A number of such models have been constructed for a variety of insect pests (Davis and others 1996; Fatzinger and Dixon 1996; Pitcairn and others 1992; Raffa and others 1992).

These predictive models of insect development are based upon estimates of heat required by a particular insect species to develop from one stage of its life cycle to the next. For most insects, development generally only occurs within a species-specific, physiologically set range of temperatures. Temperatures above and below this range represent upper and lower developmental thresholds and constitute temperatures at which development slows or ceases. Between these thresholds, the total amount of heat required by an insect to develop from one stage to the next is expressed in degree-days (DD). Degree-days represent the accumulation of temperature over time and are typically calculated above the lower developmental threshold. With knowledge of how many DD are required for the completion of a particular life stage, predictions can be made as to when that stage would be expected to be present in the field.

At present, there is no generally accepted method of determining when CLB adults will first appear in the field. Nor have models been validated to predict when subsequent life stages and generations will be present in the field. The objectives of this study were 1) to compile existing information regarding estimated developmental thresholds and DD requirements for the CLB and 2) to determine the validity of these estimates in the field as predictors of CLB presence and activity.

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Table 1— Lower developmental thresholds and degree-day estimates for the cottonwood leaf beetle (*Chrysomela scripta*) compiled from various sources

Source	Lower developmental threshold	Degree-day estimate (egg – adult)
Burkot and Benjamin (1979)- Wisconsin	10.8 °C	257 ± 26.0
Jarrard and others (Unpubl.)- Iowa	8.6 °C	282 ± 16.9
Pope and Nebeker (Unpubl.)- Mississippi	11.8 °C	281 ± 12.2

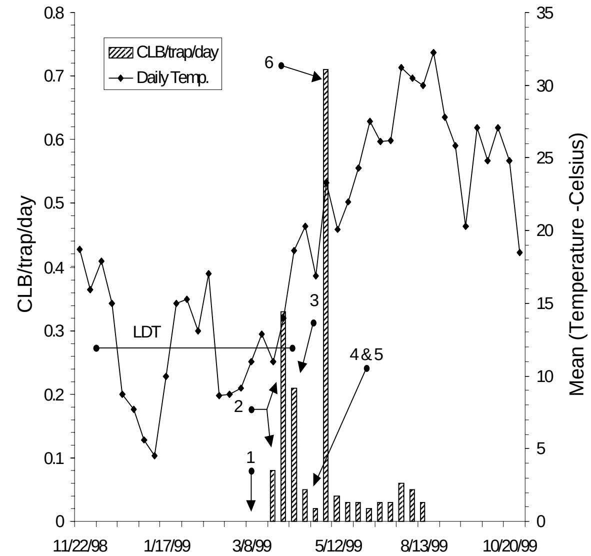

Figure 1—Number of cottonwood leaf beetle adults trapped in relation to average daily temperature: 1) overwintering adults active and present, 2) copulating adults and egg masses present (3/25/99 - 0 DD), 3) CLB larvae present in large numbers, 4) most larvae in pupation at this time, 5) pupal stage continues, and 6) first generation adults eclose in large numbers (4/29/99 - egg to eclosion 280 DD).

METHODS

Information regarding the developmental rate of the CLB was obtained from three independently conducted studies (table 1). All three studies examined the effects of a series of constant temperatures on the developmental rate of laboratory-reared CLB. Each study yielded slightly different lower developmental thresholds (LDT) and DD estimates for total preimaginal development. Two of the studies also determined DD requirements for completion of specific CLB life stages (table 2).

Study Site and Insect Sampling

Evaluation of the validity of these DD estimates in the field was conducted during 1999 at a three-year old cottonwood plantation within the Fitler Managed Forest (Crown Vantage) in west central Mississippi (Issaquena County). Cottonwood leaf beetles were monitored using modified boll weevil traps and visual observations. Basic trap layout consisted of eight trap lines spaced approximately 150 meters apart. Each trap line consisted of five traps along with one control point. Each trap was attached to the top of a 3 meter PVC pole. The control point consisted of a PVC pole without a trap. A control point was added to determine if the presence of a trap resulted in increased CLB damage to surrounding trees. Trap lines were installed 25 meters into the plantation and placed between rows of trees. The traps and control point for each trap line were randomly placed 10 meters apart within a line extending into the plantation. Trap lines at both sites were established on March 5, 1999. Traps were checked for adult CLB and trees along each transect were examined for CLB life stages on a weekly basis. Trap catches at all sites were standardized to number of CLB/trap/day. Monitoring for the CLB ceased by early November 1999.

Table 2— Comparison of degree-day estimates for specific cottonwood leaf beetle (*Chrysomela scripta*) life stages

	Degree-day estimate		
Stage	Fitler, MS	Pope and Nebeker	Jarrard and others
Egg	101	74	62
Larvae	79	127	174
Pupae	100	80	46

Calculation of Degree-days

Accumulation of DD for this CLB population began with first observation of CLB egg masses on the trees (0 degree-days). Daily maximum and minimum temperatures for this site were obtained from the National Climatic Data Center. The closest reporting station to Fitler was in Vicksburg, MS (Warren County) approximately 48 kilometers away. Daily temperatures and DD were calculated in Celsius. We used the LDT of 11.8ºC developed by Pope and Nebeker (unpubl.) to calculate DD for this CLB population. This estimate was appropriate for our validation efforts as Pope and Nebeker (unpubl.) collected CLB from this location to establish their colony at Mississippi State University. The following formula was used to calculate DD:

$$DD = [(m^1 + m^2)/2] - t$$

Where DD represents the degree-days accumulated over a 24 hour period, m^1 the maximum temperature over the 24 hour period, m^2 is the minimum temperature for that 24 hour period above the LDT, and t the LDT for the species in question (Pedigo and Zeiss 1996).

RESULTS AND DISCUSSION

Over the spring and summer of 1999 we observed the emergence of overwintered adults, copulation, oviposition of eggs, larval feeding, pupation, and eclosion of first generation adults. Figure 1 depicts trap catches of CLB adults in relation to average daily temperature. It is evident from this graph that no adult CLB were trapped until average daily temperatures rose above the LDT of 11.8ºC.

Adults emerging from their overwintering sites were first trapped March 18, 1999 after an accumulation of 136 DD with DD accumulation beginning Dec. 1, 1998. Numbers of adult CLB trapped increased a few weeks later (March 25, 1999). This increase roughly coincided with observations of large numbers of copulating pairs and ovipositing females. Numbers of adult CLB trapped and observed on trees declined after that date. As overwintering adults passed away and trap numbers declined, first generation offspring passed through their various life stages. Numbers of adults trapped reached their highest level on April 29, 1999 coinciding with the eclosion of first generation adults.

Twenty-six DD were calculated (figure 1) from a start date of March 25, 1999 as that date marked the first observation of large numbers of CLB egg masses. Accumulation of DD ceased on April 29, 1999 coinciding with eclosion of first generation adults. Based on our observations, this CLB population required approximately 280 DD to complete development (egg – adult). From eggs to larvae 101 DD, from larvae to pupae 79 DD and from pupae to new adults 100 DD (figure 1).

Degree-days required to complete each life stage (egg, larvae, pupae, adult) were also calculated and compared to those of Pope and Nebeker (unpubl.) and Jarrard and others (unpubl.). Whereas total number of estimated DD required for complete development are similar, there is somewhat more variation among the various life stages (table 2).

Our field estimate for complete CLB development corresponds almost perfectly with the predicted estimates of Pope and Nebeker (unpubl.) and Jarrard and others (unpubl.). Both estimates, 281 DD and 282 DD, respectively, occurring just one calendar day past ours. The minimum predicted estimate derived by Burkot and Benjamin (1979) of 257 DD was reached two calendar days prior to our field estimate. The estimate of 280 DD we obtained best coincides with an observed peak in first generation eclosion. Since our observations were only conducted weekly it is very likely that first generation CLB were eclosing prior to 280 DD. Although promising, additional efforts need to be put toward validating these models in the field before reliable predictions can be made.

SUMMARY

Based on this limited data, current temperature-dependent growth models hold promise for predicting the occurrence of first generation adult CLB in the field. However, predicting the appearance of specific life stages may be more difficult as evidenced by the variability in degree-day requirements we observed among our own, and others, estimates.

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THE EFFECTS OF THINNING ON BEETLES (COLEOPTERA: CARABIDAE, CERAMBYCIDAE) IN BOTTOMLAND HARDWOOD FORESTS

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Abstract— The responses of two groups of beetles, ground beetles (Carabidae) and longhorned beetles (Cerambycidae), to a partial cutting technique (thinning) applied to major and minor stream bottom sites in Mississippi were examined. Species diversity of ground beetles and longhorned beetles was greater in thinned stands than unthinned stands two years following thinning. Higher diversity of ground beetles in thinned stands was primarily attributable to the presence of species that prefer open, disturbed conditions. Longhorned beetles that use dead wood as larval host material dominated collections in thinned stands. Although the two beetle groups examined seemed to favor certain habitat conditions brought about by thinning, how other invertebrates (litter fauna, herbivores) respond will require additional investigation.

INTRODUCTION

Terrestrial insects represent an integral component of bottomland hardwood forests yet they have rarely been considered in light of their response to forest management. Insects are known to play a number of important roles (pollination, nutrient cycling, predation) in forest systems and represent a vital food source for other organisms (Janzen 1987; Packham and others. 1992). Although little studied in these settings, insects have the potential to provide a great deal of information regarding bottomland hardwood forests. However, an obstacle confronting many insect-related projects is the overwhelming diversity of species that can be collected (Disney 1986).

As an alternative to sampling all insects, assemblages of select species representing different ecological or functional roles have been suggested for use as monitoring tools or indicators of environmental change (Kremen and others 1993). Beetles (Coleoptera) are considered well suited for such purposes as they display a wide range of functional roles (herbivores, predators, fungivores), are easily sampled through a variety of passive-trapping methods, and good taxonomic information exists for many families (Hutcheson and Jones 1999).

In bottomland hardwood forests, studies evaluating beetles as indicators of environmental change are rare. Most studies conducted thus far have taken the form of faunal surveys (Allen and Thompson 1977; Goff 1952; Grey 1973; Shelford 1954) or examined the influence of natural disturbances on beetles and other terrestrial arthropods (Gorham and others 1996; Uetz and others 1979). In one of the few examples, Thompson and Allen (1993) investigated the response of ground beetles (Carabidae) to different site preparation techniques applied to a clearcut bottomland hardwood stand. In their study, they identified ground beetle species considered to be indicative of disturbed conditions in bottomland hardwood forests.

The objective of this study was to investigate the impact of the partial cutting technique, thinning, on species diversity and abundance of two beetle families in bottomland hardwood forests. Ground beetles were included as one of the target taxa. Ground beetles have generally been regarded as a good group through which to evaluate habitat change (Gardner 1991; Niemelä and others 1993; Thiele 1977). The majority of ground beetle species are predaceous feeding on other invertebrates. Through patterns in their diversity and abundance, ground beetles can provide indirect information regarding the status of their prey and how alterations in habitat conditions affect them (Day and Carthy 1988).

To gauge the impact of thinning from another ecological perspective, longhorned beetles (Cerambycidae) were selected as the second target group. Most longhorned beetle species are xylophagous, feeding on trees, shrubs, and woody vines. While some longhorned beetles feed on healthy woody plants, most species feed on dying or dead woody material, playing important roles in the fragmentation and breakdown of dead wood (Fellin 1980). Due to their dependence upon dead wood, longhorned beetles have the potential to serve as potentially sensitive indicators of forest conditions (Yanega 1996). Evaluation of how both of these groups of beetles respond to the thinning process should provide insight into how their respective habitats are effected, and what that might portend for other members of the bottomland fauna.

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METHODS

Study Site

This study was conducted in bottomland hardwood stands within major and minor stream bottom sites in Mississippi. The major stream bottom site was located in the Delta National Forest (Sharkey County) in west-central Mississippi. Dominant tree species included sweetgum (*Liquidambar styraciflua*), willow oak (*Quercus phellos*), Nuttall oak (*Q. nuttallii*), sugarberry (*Celtis laevigata*), and various elms (*Ulmus* spp.). Treatments at this site consisted of a commercial thinning applied in 1997 and an unthinned control. The minor stream bottom site was located on private land in Monroe County in northeastern Mississippi. Dominant tree species consisted of willow oak (*Q. phellos*), sweetgum (*L. styraciflua*), and elms (*Ulmus* spp.) Treatments applied at the minor stream bottom site also consisted of a commercially thinning applied in 1997 and an unthinned control. Thinnings applied at both sites removed poorly formed, diseased, and otherwise unmerchantable tree species and favored well-formed sweetgum and oaks to improve quality of the residual stand.

Beetle Sampling

Sampling for ground beetles and longhorned beetles was conducted in 1999, two years post-thinning. Ground beetles were sampled using pitfall traps. Twelve pitfall traps were placed along transects in each thinned and unthinned stand. Individual pitfall traps were placed 10 meters apart and consisted of two 1.8 liter plastic containers. One container was sunk flush with the ground as a liner and the second container placed into it. Traps were filled with 4-6 centimeters of propylene glycol as a preservative and killing agent. A number of holes were punched in the bottom of the second plastic container to serve as a sieve for removal of insects from traps. A 0.1 meter2 wooden roof supported by nails was placed over each pitfall trap to prevent flooding by rainwater. Traps were operated continuously from April to October 1999. Captured ground beetles were removed from pitfall traps every two weeks and stored in vials containing 70 percent ethanol. All collected specimens were identified to species.

Longhorned beetles were sampled using Malaise traps and barrier traps (flight-intercept traps). Malaise traps are large tent-like structures that passively trap low-flying insects and collect them in a container filled with a preservative/killing agent (Townes 1972). Collecting containers were filled with 70 percent ethanol. One Malaise trap was placed in each thinned and unthinned stand. Traps were oriented in a north-south direction with collecting heads facing south.

Barrier traps, modified from Økland (1996), consisted of two perpendicular clear plastic sheets (35 centimeters x 40 centimeters) attached to a collecting container (33 centimeters in diameter). Collecting containers were filled with 3-5 centimeters of propylene glycol. A clear plastic roof was placed on top of the intersecting sheets to prevent rainfall from entering the collecting container. Individual traps were hung between two trees at a height of approximately 1.5 meters. Five barrier traps were placed in each thinned and unthinned stand with 10 meters between individual traps. Malaise and barrier traps were operated continuously from April to October 1999. Insects from both trap types were collected every two weeks. Longhorned beetles were removed from trap catches, stored in 70 percent ethanol, and identified to species.

To evaluate longhorned beetle activity in thinned and unthinned stands, we determined the larval host preferences of collected species. Species were assigned to one of four host groups; 1) healthy hosts – species feeding on healthy woody plants, 2) weakened/stressed hosts – species feeding on woody plants weakened by disease, injuries, or other causes, 3) dead/decaying hosts – species feeding on downed or standing dead trees and branches in various stages of decay, and 4) unknown hosts – species for which larval host preference is unknown. Host preferences were compiled from Craighead (1923), Hanula (1996), Solomon (1995), and Yanega (1996).

Statistical Analyses

Species diversity of ground beetles and longhorned beetles was evaluated using rarefaction (Simberloff 1972). Rarefaction estimates the number of species in a random subsample to the entire sample. The resulting value can then be interpreted as a measure of diversity because the technique takes into account both species richness and abundance. Numbers of individuals were compared among treatments and study sites using analysis of variance (ANOVA). For longhorned beetles, distribution of numbers of individuals representing each functional group was compared between thinned and unthinned stands (pooled data) using a Chi-square test.

RESULTS AND DISCUSSION

Ground Beetle Diversity and Abundance

Overall, 13 species of ground beetles were collected from the major stream bottom site. Eight species were collected from the minor stream bottom. Species diversity, as estimated by rarefaction in a sample of 50 individuals, was greater for thinned stands than unthinned stands in both major and minor stream bottoms (figure 1). Higher diversity in the thinned stands is mostly reflective of the presence of a number of ground beetles species typical of open, disturbed habitats. The large, predatory ground beetles *Calosoma scrutator* and *Pasimachus punctulatus*, along with *Harpalus pennsylvanisus* were only collected from thinned stands. *Calosoma scrutator* is a species generally found in open hardwood forests, while *P. punctulatus* and *H. pennsylvannicus* are species typical of open, grassy fields.

Thompson and Allen (1993) suggest that finding ground beetles species such as these in bottomland hardwood forests is indicative of disturbance. Presence of these species suggests that the thinning operation did alter habitat conditions in these stands. With the removal of large number of trees, thinned stands are more open than unthinned stands, possessing a sparse understorey. As a result, more sunlight reaches the forest floor, leading to somewhat drier conditions and promoting increased growth of grasses and herbaceous vegetation. There are a number of published examples where disturbances created by silvicultural practices increases ground beetle species diversity by increasing habitat complexity (Beaudry and others 1997; Niemelä and others 1988; Parry and Rodger 1986). In those cases, as well as here, much of that increase is attributable to the colonization or increased activity of species characteristic of open, dry conditions.

However, thinning operations did not appear to effect habitat conditions so severely that species from unthinned stands were restricted from thinned stands. *Brachinus alternans* is a species common in closed-canopy bottomland hardwood forests and has been considered to be indicative of undisturbed stands (Thompson and Allen 1993). This species was the most commonly collected ground beetle at all sites and was present in larger numbers in thinned stands. In addition, total ground beetle abundance did not differ significantly between thinned and unthinned stands (F = 1.426; d.f. = 1,24; P = 0.2440). Based on this, the supposition can be made that the thinnings conducted two years prior did not negatively impact populations of the ground beetle species examined.

Longhorned beetle Diversity and Abundance

A total of 17 species of longhorned beetle were collected from the major stream bottom site, while 23 species were collected from the minor stream bottom. Species diversity, as estimated by rarefaction in a sample of 50 individuals, was greater for thinned stands than unthinned stands in both major and minor stream bottoms (figure 2). Unlike ground beetles, abundances of longhorned beetles were significantly higher in the thinned stands (F = 4.757; d.f. = 1,46; P = 0.0343) than unthinned stands.

All longhorned beetle species collected at both sites feed on woody plant tissue as larvae. When compared to unthinned stands, thinned stands contained significantly higher numbers (χ^2 = 26.803; d.f. = 2; P = <0.0001) of species that feed on dead/decaying wood and weakened/dying woody plants (figure 3). Thinned stands also contained fewer numbers of species that feed on healthy hosts. The most commonly trapped longhorned beetle in both thinned and unthinned stands was *Elaphidion mucronatum*. *Elaphidion mucronatum* feeds on the dead branches of a variety of hardwood species and was collected more frequently in thinned stands. Other dead wood feeders present in higher numbers in the thinned stands included *Typocerus zebra*, *Stenosphenus notatus*, *Doraschema cinereum*, and *Enaphalodes atomarius*. Thinning operations at both major and minor stream bottom sites left behind large amounts of logging slash in the form of branches and harvest tops. Such material represents suitable host material for these species, as well as other beetles (Buprestids, Scolytids, Platypodids) that rely on dead wood as food or habitat.

The most commonly collected species feeding on weakened/dying hosts were *Neoclytus acuminatus* and *Xylotrechus colonus*. *Neoclytus acuminatus* feeds on the sapwood of weakened, dying, and recently dead hardwood trees, while *X. colonus* feeds on phloem of a number of hardwood tree species. These species were also collected in unthinned stands but in lower numbers. Higher abundances of these beetles in thinned stands again most likely reflects input of dying and dead woody material from the thinning operation. Higher abundances of these species may also be attributable to damages to the residual stand resulting from logging wounds.

During thinning operations, damage to the residual stand may result. Wounding to the residual trees generally occurs when a harvested tree falls into a residual tree, or when logging equipment causes damage to the residual stems. At the major stream bottom site, logging wounds were especially high in the thinned stand, with 84 percent of the

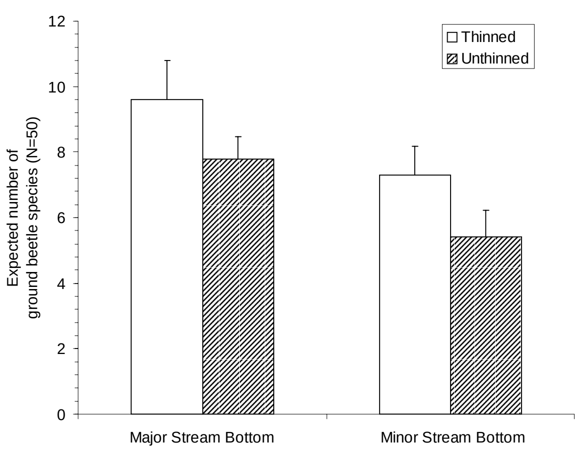

Figure 1—Ground beetle species richness, as estimated by rarefaction, in thinned and unthinned stands at major and minor stream bottom sites in Mississippi.

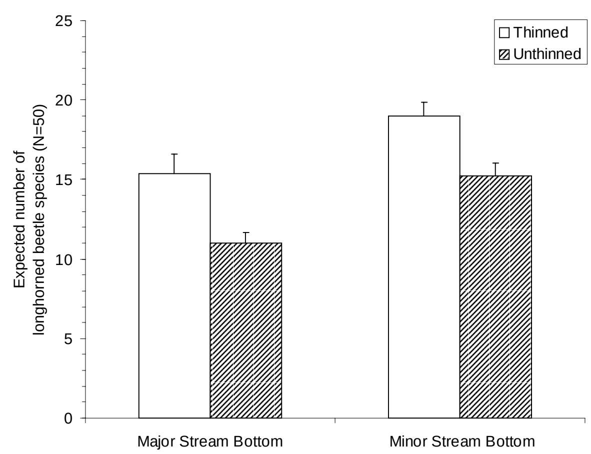

Figure 2—Longhorned beetle species richness, as estimated by rarefaction, in thinned and unthinned stands at major and minor stream bottom sites in Mississippi.

residual stems damaged in some way (Nebeker and others 1999). Wounds to the bole, roots, and branches can provide places for insects to enter and serve as infection courts for pathogens. Post-thinning surveys at this site have since shown that borer wounds have increased in the thinned stand, with many of these occurring on logging wounds (Nebeker and others 1999). In the case of insects, wounded trees are known to release volatile compounds that attract certain wood-boring beetles (Dunn and others 1986). Reduction of logging wounds might be expected to have a concomitant effect on reducing wood-boring beetle activity.

Longhorned beetle species feeding on healthy hosts were few in number. All species collected were twig pruners and borers, such as *Anelaphus parallelus*, *Oberea tripunctata*, and *Psyrassa unicolor*. These species were present in similar numbers in thinned and unthinned stands.

CONCLUSIONS

Both groups of beetles exhibited some response to thinning. Certain ground beetles responded to habitat changes brought about by the thinning process (open, disturbed conditions), whereas longhorned beetles responded to the input of dying and dead wood in the form of logging slash. Intermediate levels of disturbance are thought to enhance species diversity by increasing habitat structural complexity (Connell 1978). In the case of both of these beetle families, species diversity and abundance were increased to some degree. Increased diversity and abundance of these insects could be expected to have ramifications for other faunal groups. Other invertebrates that prefer open, disturbed conditions would also be expected to increase in thinned stands, along with species that use dead wood as habitat or a food source. In addition, those insect species that take advantage of weakened or wounded trees clearly benefit if logging damage to the residual stand is great. With increases in certain insect populations, predators (birds, reptiles) of these groups might also be expected to increase their foraging activity in thinned stands.

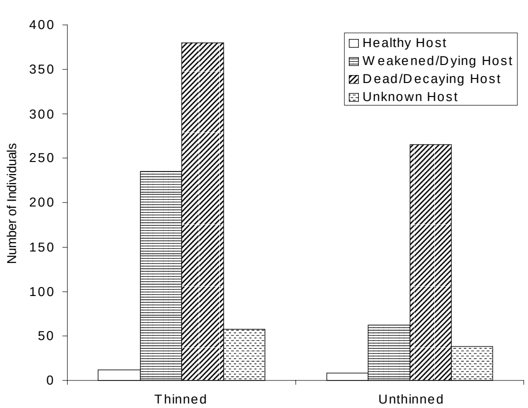

Figure 3—Larval host preferences of longhorned beetles collected in thinned and unthinned stands (pooled data) at major and minor stream bottom sites in Mississippi.

However, how long certain groups can maintain higher abundances is uncertain. Although longhorned beetles were present in higher numbers in the thinned stand, presumably due to the increased amount of host material (dead wood). The majority of dead wood left behind by the thinning operation was not large diameter material, rather it was smaller diameter branches. This material will eventually decay and reach stages where it is no longer useful to many of the longhorned beetles we collected. The thinning operation was designed to improve the quality of the residual stand and therefore diseased and undesirable trees were removed leaving a healthier stand. Those trees that were removed were trees that could have contributed to dead wood volume in the future. Consequently, dead wood input might be expected to be lower in thinned stands than unthinned stands over time. If that is true then longhorned beetle numbers in thinned stands may reach numbers comparable to or lower than unthinned stands.

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TIP-DIEBACK IN YOUNG LOBLOLLY PINE PLANTATIONS

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Abstract— Dieback of loblolly pine (*Pinus taeda* L.) has been observed in certain intensively managed plantations throughout the South. There are two distinct types of dieback; winter dieback usually appears in February and March while summer dieback appears in July (or later) and increases during the fall. Both types have very high levels of K in terminal shoots. Winter dieback progresses in a "top-down" pattern while summer dieback progresses in a "bottom-up" pattern. Winter-dieback appears to be related to freezes and growth rate as slower-growing wildlings in the plantation almost never exhibit dieback. Freeze injury (brown cambium) is sometimes observed in the stem (at breast-height) and in the terminal shoot. Often the terminal pith turns brown. One fast-growing family, 7-56 from the Coastal Plain in South Carolina, is sensitive to freezes and is prone to tip-dieback. Although winter dieback is most noticeable in plantations, it also occurs on open-grown trees that are growing in weedy, non-fertilized areas. Land managers have grown accustomed to this dieback in rapidly growing plantations that are 2 to 5 years old. On some soils, summer dieback appears to be exacerbated after fertilization with macronutrients. There is currently no consensus as to the cause of this phenomenon but we believe that growth rate, freezes, K, and B may be involved. This paper reviews some of the literature on dieback on pines and proposes some hypotheses to test.

INTRODUCTION

For more than 30 years, a disease of unknown etiology has been observed on fast-growing plantations of loblolly pine. The first reported cases were made by Doug Crutchfield at Georgetown, South Carolina (Clark 1972). Terminals of 4-year-old loblolly pine died back and subsequently, one or more lateral branches assumed dominance. It was concluded that the most likely explanation was due to freeze injury. "The trees were young. They were growing at a rapid rate due to good site conditions, hence any fall flush of growth probably would not have hardened-off in time to be protected from early frost."

Dieback ranges from Virginia to Florida and west as far as Louisiana. Many cases involved intensively managed plantations planted with family 7-56. As more cases were investigated, it became apparent that there was no consensus as to the cause of the dieback. The objective of this paper is to review the current state of knowledge and to propose alternative hypotheses to explain this phenomenon.

SYMPTOMS

There are two types of dieback: winter and summer. Winter symptoms appear after several warm days following hard freeze events. Although the freeze event may occur in mid-December or in January, symptoms in Alabama typically begin to appear in late February and March. On some trees, symptoms begin to appear in April. The date of the first appearance of winter symptoms will vary with both year and latitude. There is a "top-down" pattern of symptom progression; necrotic tissue first appears at the top of the shoot. On some trees, the pith of the terminal shoot is necrotic and affected needles are typically entirely necrotic. The terminal shoot of affected trees usually is easy to snap-off, indicating a lack of lignification. Although there are no reports of wide-spread dieback in 10-year-old plantations, open-grown trees that are 10 to 18 years old (or older) have shown signs of winter dieback. Pictures of winter dieback are found at: www.forestry.auburn.edu/south/tipdieback.html.

When new needles develop in April, they appear unaffected. By mid-summer, necrotic needles have fallen off and many stands appear to be growing normally. Upon close examination, some trees show dead terminals with a lateral bud expressing dominance. At some locations, the entire 1 m of the top is dead on a few trees and the crown develops a bushy appearance. Casual observations suggest soil type is not related to the occurrence of winter symptoms.

On some sites, dieback occurs during the summer and fall. Summer-dieback can appear in July and gradually increases over the next several months. These symptoms develop in a "bottom-up" pattern. By September, the 3rd flush may have 50 percent of the needle length affected while needles on the 5th and 6th flush are symptom free (Martin and Blakeslee

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Table 1— Seedbed density, mean root-collar diameter (RCD) and visual freeze damage estimates (percent of seedlings) for 60 seedlings from five seedlots at a nursery in Alabama in February 1996. A –9° C freeze occurred on January 19 and a –13° C freeze occurred on February 5

Family	Density	RCD	Damage
	#/m2	mm	%
7-56	237	5.3	97
12-42	215	5.6	27
1-82	237	5.4	15
1.5 orchard mix	215	5.0	22
2.0 orchard mix	226	4.7	13

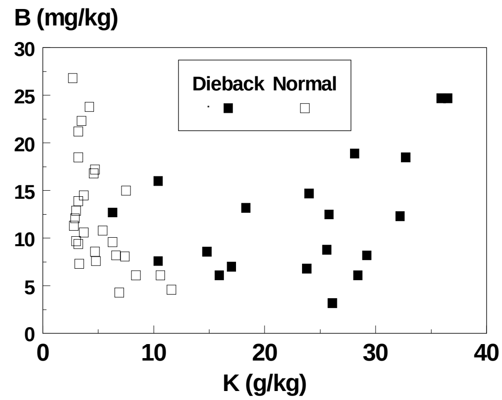

Figure 1— Concentrations of B and K in the foliage of the terminal shoots from normal (open squares) and symptomatic (closed squares) loblolly pines exhibiting winter dieback in Alabama. Each point represents one tree.

1998). By mid-November, the 5th and 6th flush will have affected needles. Necrosis appears on needle tips first and then progresses down the fasicle. On each needle, there is a sharp transition from necrotic tissue to living tissue and the distance from the tip to the transition line is the same on all three needles. On some trees, the terminal buds die and dry out. On a few trees, the terminal growth is deformed and the lateral branches form a "nest-like" appearance (Martin and Blakeslee 1998).

For both winter and summer symptoms, the probability of occurrence in intensively-managed plantations is highest 2 to 5 years after planting and then appears to decline with age. Some shoots with dieback have many 4- and 5-needle fasicles. As trees get older and larger, competition increases and the incidence of dieback decreases.

The symptoms have a genotypic component since fast-growing families are more susceptible than others. In particular, family 7-56 often shows winter dieback symptoms and on certain sites, has exhibited summer dieback symptoms. Wildlings in the same plantation almost never show dieback symptoms. Slash pine (*Pinus elliottii*) does not appear to be affected in intensively managed stands.

SIX HYPOTHESES

Tip-dieback in intensively managed plantations can likely be explained by one of the following hypotheses: 1) freeze injury; 2) K imbalance; 3) B deficiency; 4) some other abiotic agent; 5) a biotic agent. Since there are two types of dieback, it is possible dieback is; 6) caused by two independent factors.

The Freeze Injury Hypothesis

Winter dieback symptoms might be simply explained by freezing temperatures as suggested by Clark (1972) 30 years ago. Low temperatures that cause injury to pines will vary with the amount of warm weather that precedes the freeze (Mexal and others 1979). For example, a –4° C freeze at a nursery can injure loblolly pine needles in November (South and others 1993). In late December or early January, it may require a –7° C freeze. However, if loblolly seedlings are from a northern seed source and are well acclimated (with no succulent tissue), a –16° C freeze in late-December might cause little visual injury to seedlings in a bare-root nursery. The degree of freeze injury will depend on how many cells in the cambium are actively dividing at the time of the freeze. Winter dieback of Corsican pine (Pinus nigra var. calabrica) is more likely to occur when a February freeze of –7° C follows a mild period than when a –14° C freeze follows a cold January (Read 1967).

Some loblolly families can be injured at –5° C (Hodge and Weir 1993) and family 7-56 is susceptible to freeze injury (table 1). Certain individuals within this family are more freeze sensitive than others. On January 26, 1999, the temperature at Auburn, AL dropped to –7° C and symptoms were noticed in two intensively managed 7-56 plantations at the end of February. Further investigations revealed freeze injury symptoms (brown tissue) under the bark at breast height.

One year later, on December 21, 2000, temperatures at Auburn, AL dropped to –10° C and dieback symptoms were noticed on several open-grown trees (ages > 10 years) two months later on February 24, 2001. Three trees were located on the campus of Auburn University. Intensively managed plantations (7-56) also showed symptoms.

At Waycross, GA, temperatures dropped to –7° C (December 21, 1996) and summer dieback symptoms were noticed on an intensively managed plantation (7-56) seven months later in July (Martin and Blakeslee 1998). This plantation was planted in December, 1995 and, therefore, the trees were about 2.5 years old from seed when symptoms appeared. Concentrations of macro and micronutrients in the terminal were higher in the affected needles than in unaffected needles. Symptoms were observed on trees ranging in height from 0.5 to 3.6 m.

The Potassium Imbalance Hypothesis

High K in foliage from affected shoots is a unifying trait for both winter and summer dieback. When plotted together, it is apparent that dieback is more related to high K levels (>10 g/kg) than with low B (figure 1). In some cases, the foliar K levels are 4 to 10 times higher than normal, therefore some wonder if there is an error in analysis. Terminal shoots of 7-56 seedlings contain high levels of K while lower branches are normal (table 2). Terminal shoots and branches of wildlings also have normal levels of K even though treated with the same herbicides and fertilizers as adjacent planted trees. The lack of high K in wildlings indicates a genetic basis; likely related to growth rate.

At one site, newly planted 7-56 seedlings were fertilized in March, 1996 with 56, 12 and 23 kg/ha of N,P,K, respectively, and summer dieback symptoms appeared in July of 1997. High concentrations of K were observed in September, 1997 with the mean of symptomatic shoots approaching 24 g/kg (Tim Martin, pers. Comm.). One sample had a value of about 48 g/kg K which is likely a record for loblolly pine. All elements were above commonly accepted "critical" levels. Although K toxicity is not known to occur in pine trees, fertilization with K can sometimes increase dieback symptoms (Kurkela 1983). At Bainbridge, GA, summer dieback symptoms were much lower after K was removed from fertigation (Tom Cooksey, pers. comm). Several scientists question the belief that high K levels in pine shoots do not cause nutrient imbalances. In fact, some believe that high K:Mg ratios can affect fast-growing pines (Beets and Jokela 1994). At one location, the K:Mg ratio in winter dieback shoots was 25 (table 2). Since high K values in foliage is obtained from a range of soil types (and sometimes from non-fertilized trees), we hypothesize that freeze injury in the cambial zone results in high K values in the shoot.

The Boron Deficiency Hypothesis

Some observers have noted a similarity to dieback symptoms caused by a deficiency in B. Damage to buds and tip dieback are typical symptoms of B deficiency. The pith is often completely brown and dieback symptoms may resemble that caused by pathogens (Stone 1990). Boron related dieback on pines in New Zealand typically occurs in midsummer after droughts but unusual cases of winter dieback can also occur (Will 1985).

Table 2— Nutrient content (g/kg) of selected elements in the foliage of the terminal shoots and lateral branch (height approximately 2 m) of loblolly pines in an intensively managed plantation (April 5, 2000). Dieback was observed only on the shoots of 7-56. Each mean represents a sample of three trees (means within a row having common letters are not significantly different α = 0.05)

	7-56		Wildling	
Nutrient	Shoot	Branch	Shoot	Branch
N	21.0a	20.0a	21.0a	20.0a
P	2.3a	0.8b	1.2b	0.8b
K	35.0a	3.7b	3.6b	3.6b
Mg	1.4a	1.1a	1.5a	1.0a
Ca	2.0a	2.4b	3.6a	2.8ab
B	0.022a	0.013b	0.020ab	0.016ab

Fertilization with B reduced summer dieback of loblolly pine in China (Zhu 1988, Zhou and others 1997) and reduced winter dieback symptoms in Africa (Vail and others 1961, Procter 1967). However, fertilizing the soil with B failed to ameliorate the problem in South Carolina (Clark 1974) and Alabama (personal comm. Scott Cameron). In some cases, shoots with winter dieback symptoms have B levels as high as 22 ppm (table 2). In other cases, shoots with no dieback symptoms have B levels as low as 5 ppm (figure 1).

Symptoms of B deficiency are usually characteristic, "although diagnosis may be confounded by variable foliar concentrations, erratic occurrence and possible climatic damages" (Stone 1990). In fact, "near the minimum end of the range, concentrations of apparently healthy trees may be less than those in visibly deficient trees" (Stone 1990). It should be noted that a "grossly unequal distribution" of B can exist in pine needles with high levels in the tips and low levels at the base (Stone 1990). In addition, improper sampling procedures could contaminate the foliage and could result in an upward bias.

Boron is important for lignification of tissue and non-lignified tissue is more sensitive to freezes than lignified tissue. Therefore, marginally B deficient pines can be damaged by a freeze (Kolari 1983). However, it is not clear if trees with B deficiency are actually more susceptible to the freeze or if the freeze simply caused the expression of the B deficient injury (Stone 1990). Boron may also be related to infection rate of certain diseases. Data from a greenhouse study with Eucalyptus indicated that seedlings were more susceptible to *Lasiodiplodia theobromae* when B concentrations in the leaves were below 30-35 ppm (Silveira and others 1996).

Prior to development of dieback symptoms, many of the intensively managed plantations were fertilized with N and P. Fertilization of macronutrients can sometimes induce dieback on low-B soils (Kolari 1983, Brockley 1990, Stone 1990). "Because B deficiency symptoms can develop rapidly following an interruption in B uptake, and because top dieback can have such an adverse effect on stem quality and value, it is recommended that B be added to N fertilizer when undertaking aerial fertilization projects in lodgepole pine forests when average foliar B concentrations are <15 ppm" (Brockly 1990). In the southern U.S., one company now uses a fertilizer mix that includes B along with N and P. This fertilizer combination was developed for use in intensively managed loblolly pine plantations to avoid problems with B deficiency.

Except for the high K levels in shoots, there appear to be many similarities between growth disturbances reported from Finland (Kolari 1983) and the dieback reported on loblolly pine in the U.S. The once-confusing dieback symptoms in Finland "Now appear largely, though not exclusively, due to B deficiency" (Stone 1990). Some wonder if the high levels of K in loblolly pine foliage could interfere with normal B metabolism.

The Abiotic Hypothesis

In addition to freezes and imbalances of B and K, other abiotic causes for dieback have been proposed. Some believe loblolly pine may be growing faster now than in the past due to elevated levels of carbon dioxide (Valentine and others 1999). Faster stem growth might be having an effect on the production of short-roots (Dean 2001) that might affect uptake of certain nutrients. Some allege that natural electrical point discharges from the shoot tip can interrupt the hardening process and increase freeze damage (Aurela and Punkkinen 1983). Others wonder if air pollution might cause dieback.

The Biotic Hypothesis

Lasiodiplodia theobromae is a ubiquitous facultative wound pathogen that has been associated with cankers and dieback of several trees including *Cupressus sempervirens* (Bruck and others 1990), *Eucalyptus citriodora* (Silveira and others 1996), *Liquidambar styraciflua* (Garren 1956), *Platanus occidentalis* (Lewis and van Arsdel 1976, Cooper and others 1977) and *Albizia falcataria* (Sharma and Sankaran 1988). This fungus has been found on slash pine seed in orchards (Fraedrich and Miller 1995) and on seedlings in loblolly pine and slash pine nurseries (Rowan 1982). Roy Hedden isolated this fungus from winter-dieback trees in South Carolina and Georgia and his student determined that inoculations cause dieback of 2-year-old loblolly pine seedlings (Jolley 2001).

Secondary fungi associated with dieback of loblolly in China include *Sphaeropsis sapinea* (Su and others 1991), however, loblolly pine is generally more resistant to this vectored fungus than other pines (Bega and others 1978, Swart and others 1988). Secondary insects are occasionally associated with winter dieback symptoms include Scolytid twig borers (*Pityophthorus pulicarius*) (Clark 1972).

The Two-factor Hypothesis

Due to the difference in symptom development for summer and winter dieback ("top-down" vs. "bottom-up"), it would not be surprising if two independent vectors were involved. It is possible that winter dieback is a function of freeze injury as suggested by Clark (1972). The combinations of rapid shoot growth followed by warm falls would likely increase the susceptibility of certain genotypes to injury from a –5^{o} C freeze. Freeze injury would likely increase the rate of infection from *Lasiodiplodia theobromae* while adjacent genotypes without freeze injury would not be infected.

In contrast, summer dieback symptoms appear to be less common and may be restricted to certain soil groups. Summer dieback might be due to an imbalance of nutrients resulting from either fertilization with only macronutrients, an imbalance between K and B, or perhaps an inadequate production of short feeder roots.

RECOMMENDATIONS

Only a few experiments have been conducted to test hypotheses related to dieback on loblolly pine. Trials should be conducted to determine if the high foliar K levels are a direct result of freeze injury. This might be accomplished by growing 7-56 in large containers in a heated greenhouse in Virginia and moving selected individuals outside just prior to a –10^{o} C (or colder) freeze. The foliage levels could be monitored to determine if the freeze affected nutrient levels in the shoot and sap.

Trials should be conducted to determine if K toxicity occurs on loblolly pine. Tree injectors could be used to apply potassium carbonate or potassium sulfate to 3-year-old seedlings. Rates applied should increase K levels in the foliage to 30 g/kg or greater. In addition, periodic nutrient analysis of a progeny test should be conducted to determine if 7-56 normally has high K levels in the terminal shoot.

Although a few B fertilizer trials have failed to produce beneficial effects, we have no information regarding the timing or amounts of B applied. We propose that prophylactic trials be conducted in young 7-56 plantations with the new N,P,B fertilizer (along with traditional N,P fertilizer). These trials should be conducted on the same soil groups where summer-dieback symptoms have occurred in the past. Greenhouse trials should be conducted to determine if K or B levels in loblolly pine shoots affect susceptibility to *Lasiodiplodia theobromae*.

In some conifers, dieback does not seem to cause a significant problem with wood quality (Bodner 1988). However, there is some concern that even small crooks can affect both the stumpage and lumber value. With loblolly pine, compression wood associated with dead terminals might reduce pulp yields by 1.5 to 2.5 percent (Hedden 1998). Plantations with severe winter dieback should be documented and later evaluated at harvest to determine the effects on wood quality.

SUMMARY

Evidence is yet not fully convincing for any of the above hypotheses. Each hypothesis has supporters. The next step is for scientists to conduct trials to determine the true causes of winter and summer dieback.

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GLAZE DAMAGE IN 13- TO 18-YEAR-OLD, NATURAL, EVEN-AGED STANDS OF LOBLOLLY PINES IN SOUTHEASTERN ARKANSAS

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Abstract—In late December 1998, a severe winter storm deposited 2.1 inches of precipitation on the Crossett Experimental Forest in southeastern Arkansas. Ice, in the form of glaze, accumulated on needles and branches of trees, and resulted in visual damage to sapling and pulpwood-sized pines. Within 60 days after the storm, damage was assessed within naturally regenerated, even-aged stands of loblolly pines (*Pinus taeda* L.) that ranged in age from 13 to 18 years. In all stands, >50 percent of pines were undamaged. When damage occurred in unthinned 13- and 18-year-old stands, pines were mostly affected by bending of the main stem. In thinned 15-year-old stands, damage was mainly in the form of branch loss. Stem breakage most often occurred when pines were 6 to 8 inches d.b.h. The probability of crown loss increased as d.b.h. increased; whereas, the probability of a bent main stem decreased with increasing d.b.h.

INTRODUCTION

Severe ice storms are fairly common in southeastern Arkansas, occurring three times (1974, 1979, and 1994) in 20 years (Guo 1999). During such storms, freezing rain or sleet accumulates as ice on trees. Affected trees can be uprooted, bent, or have their branches and stems broken. When ice storms cause substantial damage to pine stands, future volume production will likely be reduced and hardwoods may gain a competitive advantage over the pines (Halverson and Guldin 1995).

Since the occurrence and severity of ice storms are not predictable, landowners need information on the type and extent of damage that might be expected in their forest stands. The immediate effect of ice damage in loblolly pine (*Pinus taeda* L.) plantations has been extensively reported (McKellar 1942, Brender and Romancier 1960, Shepard 1975 and 1978, Fountain and Burnett 1979), but a literature search revealed no published information derived from natural, even-aged stands of loblolly pine. An ice storm in December 1998 resulted in eye-catching damage and gave the appearance of disaster in 13- to 18-year-old stands of naturally regenerated loblolly pines in southeastern Arkansas. This incident provided an opportunity to quantitatively evaluate the damage caused by ice in young natural pine stands.

METHODS

Study Area

Ice damage assessments were made within six natural, even-aged loblolly pine stands located within a 0.5-mile radius on the Upper Coastal Plain in southeastern Arkansas. Soils are Bude (Glossaquic Fragiudalf) and Providence (Typic Fragiudalf) silt loams with a site index of 85 to 90 feet for loblolly pine at age 50 years (USDA 1979).

Pines in these six stands represented three age classes—13, 15, and 18 years. Although shortleaf pines (*Pinus echinata* Mill.) were present in four of the six stands, their contribution was only 2 percent of total basal area. Each of the six stands contained 5 acres, and they originated on clearcut areas that measured either 660 feet by 330 feet or 1320 feet by 165 feet, with the long axes oriented north to south. Before regenerating naturally, these six areas were occupied by uneven-aged stands of loblolly and shortleaf pines that ranged up to 28 inches d.b.h. with about 100 pines per acre and about 9,000 board feet (Doyle scale) sawlog volume per acre. On four areas, merchantable-sized (>3.5 inches d.b.h.) pines were harvested in spring 1981. On two of these clearcuts, 18-year-old pine stands developed from seeds dispersed before harvest. The other two stands seeded with pines 15 years earlier after mowing a 3-year-old rough of vines, shrubs, and brambles that arose after clearcutting. The two 13-year-old stands developed from seeds dispersed during clearcutting of uneven-aged loblolly and shortleaf pines in autumn 1985.

Stand History

Once regenerated, the two 13-year-old stands and the two 18-year-old stands remained undisturbed until the ice storm of 1998. The two 15-year-old stands were intensively managed by applying herbicides to control competing vegetation for the first 5 years after pine establishment from seed, by precommercial thinning to a residual density of 500 pines per acre at age 5, and by commercial thinning from below at age 14 to leave 200 dominant and codominant pines per acre.

Before the ice storm, pine density and basal area were as follows: 1,222 stems and 124 square feet per acre in the unthinned 13-year-old stands; 200 stems and 79 square feet per acre in the commercially thinned 15-year-old

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stands; 1,192 stems and 173 square feet per acre in the unthinned 18-year-old stands. Mean quadratic d.b.h.'s were 4.3, 8.5, and 5.2 inches for the 13-, 15-, and 18-year-old stands, respectively.

Ice Storm

During 4 days (December 18-21, 1998) before the storm, weather conditions were mild, with high and low temperatures averaging 65° F and 42° F, respectively. During those 4 days, there was an accumulation of 1.2 inches of precipitation. On December 22, the high temperature was 40° F and the low temperature was 27° F. During the next 4 days, high temperatures ranged from 31 to 40° F and the lows ranged from 23 to 27° F. Between December 22 and 27, intermittent precipitation took the form of freezing rain or fine mist with a total accumulation of 2.1 inches. Ice deposits on forest vegetation were not measured, although radial thicknesses of 0.25 to 0.50 inch on pine needles, branches, and stems are not uncommon in this area (Burton 1981). The ice melted on December 27 and 28, when high and low temperatures rose to 49 and 41° F, respectively.

Measurements

Ice damage was assessed in late January through early February 1999. In the 13- and 18-year-old stands, fifty-one 0.01-acre temporary plots were systematically established. In the 15-year-old stand, damage assessments were conducted on 16 permanent 0.1-acre plots. Within these plot boundaries, each pine ≥1.0 inch d.b.h. was evaluated by type and extent of damage. The following damage categories were recognized: branch loss, crown loss, main stem broken, main stem bent, or tree root-sprung (roots loosened and the tree leaned from the base). For this study, branch loss was considered only if branch diameter was > 0.5 inch. The extent of branch and crown loss was estimated to the nearest 10 percent. Crown loss occurred when the central axis or main stem was broken. Branch loss occurred when individual branches were broken, but this category was never > 10 percent. Main stem breakage occurred when crown loss was 100 percent, and the stem broke below the lowest live branch. A root-sprung pine had large lateral roots displaced from the soil. The angle from the stem base to the terminal bud was estimated to the nearest 10 degrees for bent-stem and root-sprung damage categories. Some classes were mutually exclusive by definition: bent stem versus root sprung, and crown loss versus branch loss versus stem breakage. However, root-sprung pines or those with bent stems could also have crown and branch loss, but only two pines were classified as incurring multiple types of damage. Any mitigating circumstances (such as stem defects, forks, or damage caused by a neighboring tree) associated with a pine's damage were also recorded.

Data Analysis

Two plots, one in the 13-year-old stand and one in the 18-year-old stand, contained no pines and were dropped from analyses. To equalize the number of plots assessed for each age, the remaining 50 plots in the 13- and 18-year-old stands were grouped into 16 sets of three and one set of two based on their proximity to each other. Analyses included four severity classes: light (10- or 20-percent loss or degrees), moderate (30 to 50 percent loss or degrees), severe (over 50 percent loss or degrees), and lethal (main stem breakage or root-sprung). Only four trees were root-sprung, and all had tilts of > 60 degrees. Analysis of variance was conducted on the percentage of trees on each plot by damage type and severity class for a completely randomized design with stand age as the treatment variable. Plots were considered as pseudoreplicates (Hurlbert, 1984), which assumes that sampling error would be representative of the experimental error of true replicates. Percentage data were analyzed following arcsine square-root transformation, but only nontransformed percentages are reported. Differences among treatment

Table 1—Type and degree of ice damage in natural, even-aged loblolly pine stands in southeastern Arkansas

Type/degree of ice Damage	----------Stand age in years---------- 13	15	18	Mean Square Error	*P*
	———Percent[a]———				
Type of damage					
None	68.3a[b]	68.1a	53.6b	0.0443	0.04
Branch loss	1.8b	17.8a	0.9b	0.0098	<0.01
Crown loss	9.3a	10.3a	5.8b	0.0145	0.02
Main stem broken	1.1b	1.6ab	5.1a	0.0181	0.04
Main stem bent	19.5b	1.9c	34.2a	0.0517	<0.01
Tree root-sprung	0.0a	0.3a	0.4a	0.0024	0.42
Degree of damage					
None	68.3a	68.1a	53.6b	0.0443	0.04
Light	14.1b	24.4a	14.9b	0.0197	<0.01
Moderate	10.1a	5.0b	16.8a	0.0272	<0.01
Severve	6.4a	0.6b	9.2a	0.0245	<0.01
Lethal	1.1b	1.9ab	5.5a	0.0191	0.04

[a]Percent of all pines that were assessed.
[b]Row means followed by the same letter are not significantly different at the 0.05 level.

means were isolated using the Ryan-Einot-Gabriel-Welsch Multiple Range Test at $\alpha = 0.05$ (SAS Institute, Inc. 1989).

Logistic regression was used to test the effects of tree d.b.h. and plot basal area on the probability of damaged trees having either crown loss, stem breakage, or stem bending (Amateis and Burkhart 1996). This regression equation was based on 303 pines with moderate or severe damage in crown loss, stem breakage, or stem bending, and coefficients were calculated using the SAS procedure LOGISTIC (SAS Institute, Inc. 1989).

RESULTS AND DISCUSSION

The good news for forest landowners was that more than half the pines in these natural stands exhibited no apparent damage from the ice storm (table 1). The 18-year-old stands had a higher ($P = 0.04$) percentage (46.4 percent) of ice-damaged pines than did the 13- or 15-year-old stands. The most common damage category was a bent main stem for the 18-year-old pines (34.2 percent) and for the 13-year-old pines (19.5 percent). For pines in the 15-year-old stands, the greatest damage was branch loss (17.8 percent).

These differences among stands are attributed to the effects of thinning. Pines in the 15-year-old thinned stands were widely spaced with large crowns. Large crowns contributed to limb breakage and branch loss from ice accumulation because of their greater surface area. In contrast, pines in the unthinned 13- and 18-year-old stands were crowded with slender crowns. High pine density plus ice in these latter two stands resulted in a domino effect—as these unthinned pines began to bend from the ice, their neighbors were forced to bend in the same direction because of intertwined crowns. Of all tree and stand characteristics that contributed to ice storm damage (table 2), this neighboring-tree effect was highest ($P < 0.01$) in the 18-year-old stands (32.9 percent) when compared to the other stands. This type of damage was also greater ($P < 0.01$) in the 13- (13.6 percent) versus the 15-year-old stands (0.0 percent). In these natural stands, bole defects (such as cankers from *Cronartium fusiforme* Hedg. & Hunt) and stem forks were minor contributors to subsequent ice damage on trees (table 2).

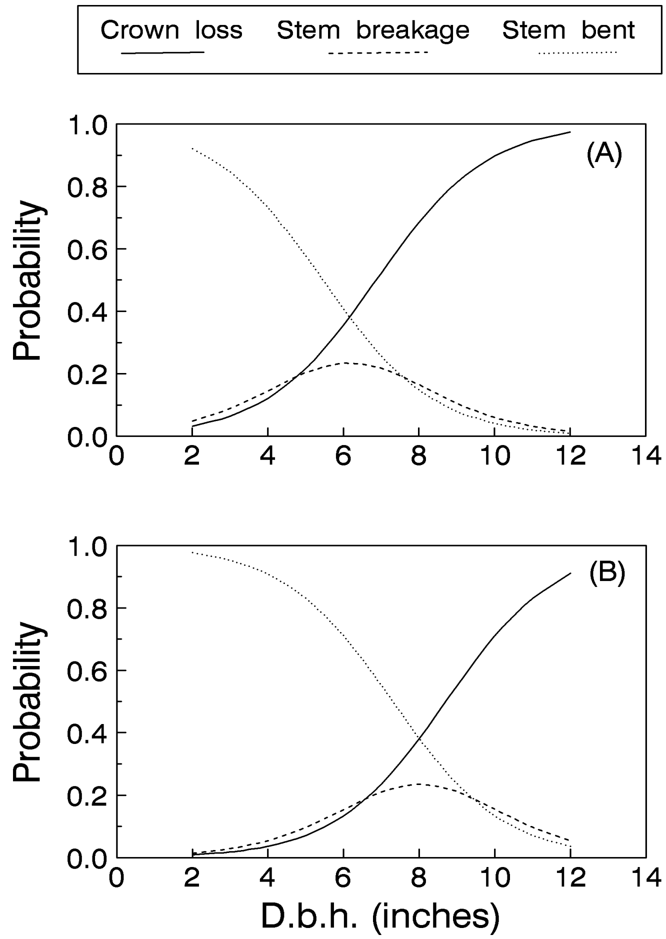

Figure 1—Predicted probabilities for crown loss, stem breakage, and stem bending caused by an ice storm in natural, even-aged loblolly pine stands at two basal-area levels: (A) 80 square feet per acre, (B) 140 square feet per acre. Results are based on 303 pines with moderate or severe damage.

Moderate to severe ice damage was greater ($P < 0.01$) in the 13- (16.5 percent) and 18-year-old (26.0 percent) stands as compared to the 15-year-old (5.6 percent) stands (table 1). Although the degree of damage rated as lethal was < 6 percent of the pines in any stand, Amateis

Table 2—Tree and stand characteristics that contributed to ice damage in natural, even-aged loblolly pine stands in southeastern Arkansas

Tree and stand characteristics	----------Stand age in years-------- 13	15	18	Mean Square Error	*P*
	Percent[a]				
None	85.3b[b]	98.8a	65.6c	0.0620	<0.01
Stem defects	0.6a	0.6a	1.3a	0.0073	0.47
Stem fork	0.5a	0.6a	0.2a	0.0040	0.59
Damage from neighboring pines	13.6b	0.0c	32.9a	0.0597	<0.01

[a]Percent of all pines that were assessed.

[b]Row means followed by the same letter are not significantly different at the 0.05 level.

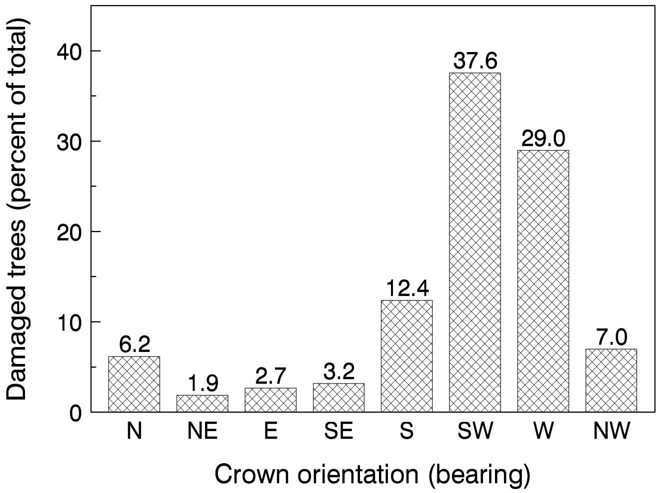

Figure 2—Crown orientation of loblolly pines that were bent, broken, or root-sprung by an ice storm in natural, even-aged stands. Results are based on 372 pines.

and Burkhart (1996) considered glaze damage that was >50 percent on loblolly pines to be so severe that the trees would soon die. Using their criterion in the present study, about 8 percent of ice-damaged pines in the 13-year-old stands and 15 percent in the 18-year-old stands would likely die.

The probability that a damaged tree will have crown loss, stem breakage, or stem bending can be determined from the following series of equations:

$$P_c = \exp(-3.106 + 0.704D - 0.022B) / \{1+ \exp(-3.106 + 0.704D - 0.022B)\} \quad (1)$$

$$P_s = \exp(-2.126 + 0.704D - 0.022B) / \{1+ \exp(-2.126 +0.704D - 0.022B)\} - P_c \quad (2)$$

$$P_b = 1-P_c-P_s \quad (3)$$

where P_c, P_s, and P_b are the probability the damaged tree will have crown loss, stem breakage, or stem bending, respectively; D is d.b.h. (inches); B is plot basal area (square feet per acre); and the regression coefficients were determined using logistic regression. All regression coefficients had Wald chi-squares of ≥26 and the probability of a larger value occurring by chance was <0.01 in all cases. The logistic regression had an R-square of 0.38.

These equations were solved for a reasonable range of d.b.h. values and two levels of basal area; the predicted probabilities are illustrated in figure 1. These equations suggest that stem breakage in natural loblolly pine stands under severe ice loading is most likely to occur at a d.b.h. of 6 inches when basal area is 80 square feet per acre or at a d.b.h. of 8 inches when basal area is 140 square feet per acre. Stem breakage is less likely at higher basal areas because the greater number of pines prevents stems from bending to the point of breaking. For both of these moderate to high basal area levels, the probability of crown loss was greater as d.b.h. increased. Conversely, the probability of stem bending declined as d.b.h. increased. These results are similar to those reported by Shepard (1975) in row-thinned loblolly pine plantations that were ice damaged in north Louisiana.

For pines that were bent or leaning as a result of the 1998 ice storm, crown orientation was generally constant. Fully 79 percent of these damaged pines had their crowns oriented in a southerly to westerly direction (figure 2), suggesting that prevailing winds during the storm were from the north and east. Consistency in the direction of lean would facilitate removal of the damaged trees through the use of directional felling.

MANAGEMENT IMPLICATIONS

After an ice storm, forest managers must determine the extent of damaged trees by conducting an inventory. Although merchantability standards vary across the South, about 5 cords of pulpwood or 1,000 board feet (Scribner scale) must be removed per acre to generate a merchantable harvest (Hyman 1985). In the present study, the volume in severely damaged pines >4 inches d.b.h. was estimated to be 0.9, 0.3, and 5.7 cords per acre in the 13-, 15-, and 18-year-old stands, respectively. Consequently, only pines in the 18-year-old stand were marked for a combination salvage and improvement thinning.

Merchantability of damaged trees may be of less importance than preventing an insect infestation. According to Hyman (1985), the greatest hazard to ice-damaged pine stands is the threat of southern pine beetles (*Dendroctonus frontalis* Zimm.). That threat is compounded by the fact that pine stands with basal areas in excess of 100 square feet per acre are highly susceptible to bark beetle infestation (Hicks 1981). In this study, basal area for the unthinned stands averaged 150 square feet per acre, thereby posing an increased risk of infestation to the remaining timber unless salvaged.

Pines in the 15-year-old thinned stands had larger mean diameters and suffered less bending but more branch loss from the ice storm than the higher density pines in the unthinned 13- or 18-year-old stands. These results suggest that early thinning in natural loblolly pine stands is advantageous by not only improving diameter growth but also by reducing the potential of catastrophic loss from periodic ice storms. Natural disturbances such as tornadoes, hurricanes, and ice storms often cause a drop in stumpage prices because of an overabundant supply of salvaged timber. But when forest landowners schedule thinnings outside the parameters of these natural disasters, they are able to take advantage of higher stumpage prices and reduce their probability of loss.

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